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LUBRICITY OF JET A-1 AND JP-4 FUELS

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13. ABSTRACT

This report describes the evaluation of an instrument that gives an indication of the lubricity of a fuel and of the results from testing Jet A-1 and JP-4 fuels with the device. The instrument is the Furey Ball-on-Cylinder. The preliminary investigation dealt with establishing the repeatability and reproducibility of the rig on pure hydrocarbons and Jet A-1 fuels. Also, the results from the Jet A-1 fuels served as the basis for a direct comparison between the wear scar diameter from the Ball-on-Cylinder and the coefficient of friction from the Bendix-CRC Lubricity Simulator. The Spearman Rank Correlation Statistic was applied to the relation and the two rigs were found to correlate at a level of significance less than .5%. For the same Jet A-1 fuels, possible correlations were examined between wear scar diameter and each physical property of the fuels. Many correlations were obtained with a definite trend established. The Jet A-1 fuels which were composed of a high percentage of heavy end hydrocarbons had the best lubricity. In a similar manner, JP-4 fuels which contained corrosion inhibitors, were tested on the Ball-on-Cylinder and the wear scar diameters obtained were compared to the fuels properties. No correlations were found.

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FOREWORD

This report was prepared by the Fuels Branch, Fuels and Lubrication Division of the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 304805, Work Unit 46. Mr. J. Petrarca, Jr., was the project engineer.

The work in this report was conducted from January 1972 to June, 1973, as part of an in-house project on fuel lubricity.

The author wishes to extend his appreciation to Dr. Goldblatt of ESSO Research and Engineering for his cooperation in the joint test program concerning the reproducibility of the Ball-on-Cylinder device. Acknowledgements with thanks are also given to Mr. M. Shayeson of General Electric for the use of his data from the Bendix-CRC Lubricity Simulator.

This report was submitted by the author October, 1973.

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1.0 Background

A fuel has many functions in a jet engine besides its use as an energy source. It is also a heat sink or coolant for oils, airframe, electronics, etc.; a hydraulic fluid; and a lubricant. This report deals with the lubricant aspect of a fuel.

In the fuel system, there are two devices, fuel pumps and controls, which are sensitive to the lubricity of a fuel. During their operation, both devices have components which are continuously in contact with the fuel and receive their lubrication from it. The fuel pumps are mainly of two types: gear and piston. A lack of lubrication to the gears or pistons will cause them to wear excessively. This, in turn, will decrease the mean time between failure of the pumps.

The fuel controls are an agglomoration of cams-on-shafts, variable orifices, spools-in-sleeves, etc. Some of these components will also wear excessively if they do not receive a satisfactory amount of lubrication. The worn components will unfavorably change the response characteristics of the control and decrease the control's required overhaul time.

A second lubricity problem also associated with fuel controls does not involve wear. The component affected is the spool-sleeve assembly. During the control's operation, if the spool is in the presence of a low lubricity fuel, an excessive amount of drag will build up as it slides inside the sleeve. This drag will cause a lag in the control's response or it may become large enough to cause the spool to stick and thereby "hang up" the control.

Currently, there are many properties of a fuel which have limits established by specifications. These specifications are for controlling the fuel's combustion characteristics (BTU's, etc.), operational requirements (freezing point, etc.), and undesirable side effects (WSIM number, etc.).

The Water Separameter Index (WSIM) is a test which was developed to control the adverse effect of surfactants in a fuel on the efficiency of the filter/separator elements which are in ground fuel handling systems. The WSIM number of a fuel may range from 0 to 100. By specifying a minimum WSIM number for the fuel, the adverse effect of the fuel on the efficiency of filter/separator elements is controlled.

On 1 October 1965, the U.S. Air Force changed its JP-4 fuel specification in order to increase the efficiency of the filter/separator elements. It raised the minimum required WSIM number from 55 to 85 and deleted the use of all corrosion inhibitors in the fuel. Since most bases were no longer supplied directly by pipelines, the corrosion inhibitors were not needed in the fuel for their original purpose. Also as an added precaution to ensure meeting this new specification, the refineries began to claytreat the fuel.

The first U.S. Air Force Lubricity problem occurred in 1965 with the use of JP-4 fuel. The time of the problem coincided with the change in the JP-4 fuel specification to delete the corrosion inhibitors. The lubricity problem involved aircraft containing the J57, J69, and J79 engines. When the pilot tried to deaccelerate the aircraft, the corresponding response from the fuel control to the afterburner was either sluggish or nonexistent.

This meant that in the extreme case, some aircraft were stuck at full throttle. When a hung-up control was examined, a spool/sleeve servo system was found to be malfunctioning. A quick solution was sought to the problem with the main effort being conducted by Webb AFB. They tested the response of fuel controls running on the JP-4 which had a WSIM of 85 and was known to have caused actual field problems, and on a JP-4 which contained corrosion inhibitors and showed no prior in-service problems. Previously hung up controls were relieved when they were operated with JP-4 which contained corrosion inhibitors. The hang-up would recur in the controls when they were operated with the higher WSIM fuel.

At this same time, the U.S. Air Force had a contract, AF33(615)-2868, with ESSO Research and Engineering which encompassed the evaluation of different lubricity test rigs. The Furey Ball-on-Cylinder device was the most promising at the time. Three field fuels were tested on it by ESSO. Fuel A had a definite lubricity field problem; Fuels B and C did not. Their results are in Table 1. Fuel A

TABLE 1

FIELD CORRELATIONS WITH BALL-ON-CYLINDER*

FUEL	WEAR SCAR DIAMETER (mm) AT LOAD			FIELD PROBLEMS
	60g	240g	1000g	
A	.31	.49	.58	Yes
B	.23	.33	.38	No
C	.22	.27	.34	No

*See Reference 1

had a substantially larger wear scar than Fuels B and C at the 1000 gm load operating conditions. Its lubricity, as rated by the device, is the worst of the three.

On 1 April 1966, in order to relieve the problem, the Air Force again changed its JP-4 fuel specification. It lowered the minimum acceptable WSIM number to 70 and made corrosion inhibitors a mandatory requirement in the fuel.

A follow-up study of the problem was conducted by Bendix in 1966 under a contract with the Air Force to evaluate the effect of lubricity agents and corrosion inhibitors as boundary lubricants on the J-57 fuel control (TJ-L2))[2]. New, rebuilt, and hung-up fuel controls were tested in the program with a claytreated JP-4 as the base fuel. When a fuel is claytreated, polar compounds which give the fuel its good lubricity by the boundary lubrication mechanism are removed. The corrosion inhibitors are known to be polar compounds. Part of their conclusion was that the TJ-L2 control is sensitive to the presence of corrosion inhibitors. The amount of sensitivity varies from control to control due to differences in finishes, wear conditions, fits, tolerances, etc. The corrosion inhibitors had their most dramatic effect on the previously hung-up controls. It would take hours of running on the base fuel to hang-up the valve; yet, it took only minutes of running on the base fuel with the added corrosion inhibitor to relieve it.

Currently, the corrosion inhibitors are qualified by a corrosion test although they are mainly used for lubricity reasons. A lubricity test is needed for the fuel which is versatile enough to accomplish three general goals: to (1) evaluate the effectiveness

of fuel additives (including corrosion inhibitors) used as lubricity agents; (2) evaluate the lubricity of field fuel samples and (3) determine the environmental parameters which affect the lubricity of a fuel. The corrosion test in its present form does not fulfill the first goal adequately and cannot accomplish either the second or third.

2.0 Introduction.

The objectives of the Air Force program on fuel lubricity are: to (1) establish a test device for measuring the lubricity property of jet fuels, and (2) determine the effectiveness of lubricity additives under different conditions.

There are many test rigs available for evaluating oils as lubricants; however, these rigs operate in the hydrodynamic lubrication region. The lubricity of a fuel is concerned with boundary lubrication. Therefore, test rigs which operate in the hydrodynamic lubrication region are not applicable for measuring fuel lubricity. Two boundary lubrication devices currently under the Air Force's evaluation as fuel lubricity test rigs are: the Furey Ball-on-Cylinder and the Bendix-CRC lubricity simulator. This report, which deals mainly with the Ball-on-Cylinder rig, is broken down into four main sections according to the following areas:

a. Repeatability of Ball-on-Cylinder. This is defined as the ability of one device to give consistent results on the same fluid at the same operating conditions and with the same operator. This was examined for hydrocarbons and Jet A-1 fuels and is discussed in Section 4.0.

b. Reproducibility of the Ball-on-Cylinder. This is defined as the ability of several devices of the same type to give consistent results on the same fluids but operated by different operators in different laboratories. This was also examined for the hydrocarbons

and fuels mentioned in Section 4.0 and is discussed in Section 5.0.

c. Correlation of Ball-on-Cylinder with CRC Bendix Lubricity Simulator. General Electric had previously tested the same Jet A-1 fuels (See 2a, above) for lubricity on their CRC-Bendix simulator. On the basis of the results from the Jet A-1's, a rank correlation between the coefficient of friction from the CRC-Bendix simulator and the linear scar diameter from the Ball-on-Cylinder was examined and is discussed in Section 6.0.

d. Correlation of Fuel Properties with Wear Scar Diameters. A variety of physical properties were known for the Jet A-1 fuels and the JP-4 fuels tested. A rank correlation was examined in Section 7.0 between each physical property of the fuels of the same grade and their lubricity as determined by the wear scar diameters.

3.0 Test Devices

Work has been done with two test rigs in this report. The primary rig under investigation is the Furey Ball-on-Cylinder. It was originally developed to study metallic contact and friction between sliding lubricated surfaces[3]. It has proved its ability to distinguish between a good and poor lubricity fuel as discussed in the Background, Section 1.0. The other rig under investigation by the Air Force is the Bendix-CRC Lubricity Simulator. The basic guidelines for the device were established by the Coordinating Research Council (CRC), and the device was built by Bendix. The guidelines called for the desire to simulate the typical valve and sleeve in the fuel control which caused the first Air Force lubricity problem. Therefore, this device is believed to correlate with field problems.

3.1 Ball-on-Cylinder

The Furey Ball-on-Cylinder rig, Figures 1 and 2, consists of a stationary ball which is perpendicular to a cylinder and is in contact with it. The ball can be loaded up to 4 Kg by dead weights. This corresponds to a Hertz pressure up to 100,000 psi. The cylinder can rotate at speeds up to 3000 rpm. The ball and cylinder are located in a rectangular test cell which has removable Teflon covers. The test cell contains 50 ml of test fuel in which the cylinder is approximately 1/3 immersed.

The environment at the point of contact between the ball and cylinder is controlled by purging the test cell for 15 minutes

Figure 1. Ball-On Cylinder

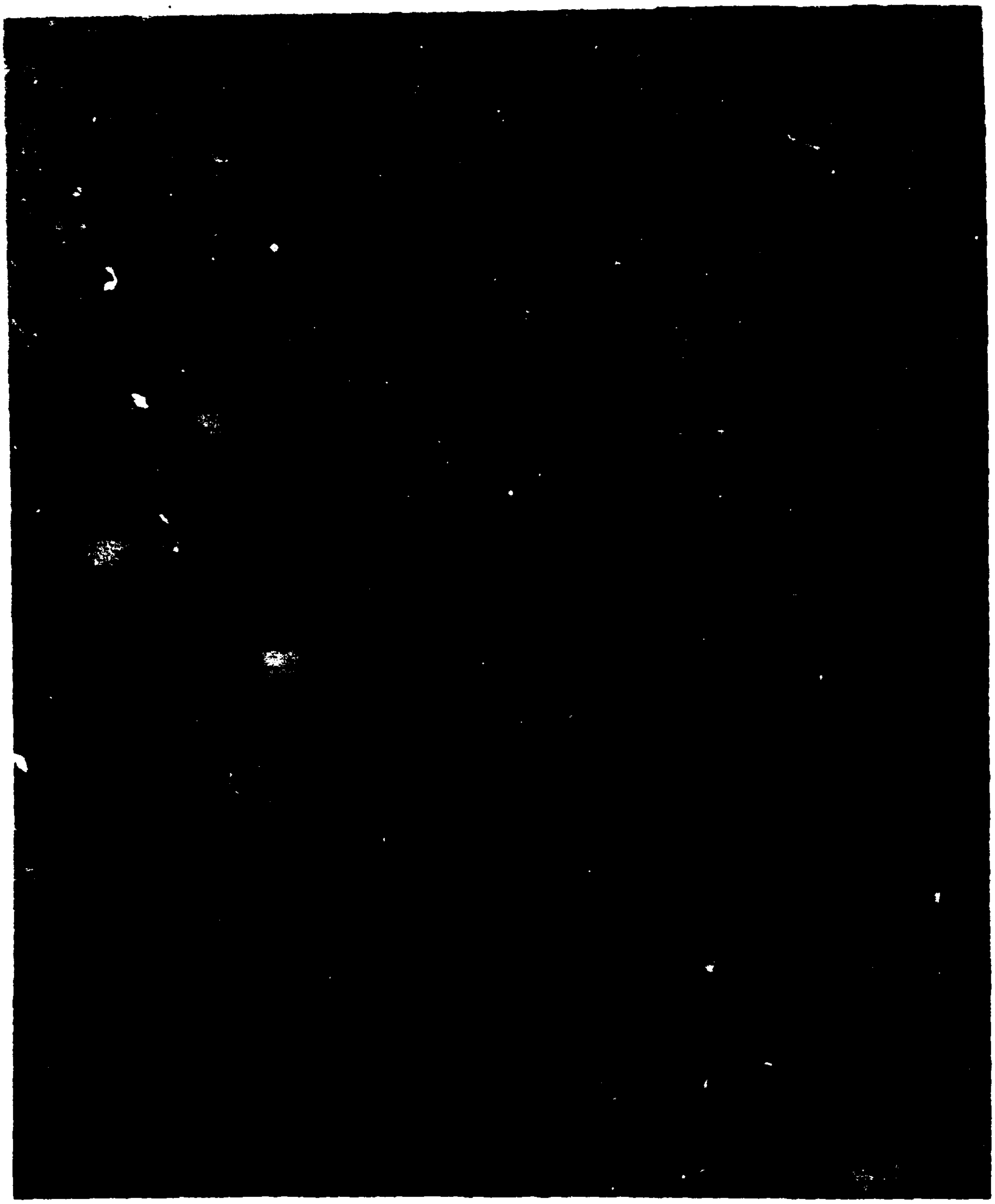

Figure 2. Ball-On-Cylinder Without Test Cell

with air at a flowrate high enough to prevent any diffusion of the atmosphere from the room into the cell; a flowrate of 0.5 ft^3/min. is sufficient. The purging can be accomplished by one of two methods. The indirect air purging method flows the air over the test fluid. The direct method involves flowing the air through the test fluid. Previous work by ESSO illustrated that the humidity and oxygen content of this environment does affect the results. In this report, all tests were run with water pumped cylinder air containing less than 20 ppm H_2O.

Three measurements are obtained from the Ball-on-Cylinder rig.

a. The dynamic friction force of the sliding ball in contact with the cylinder is measured by a Linear Variable Displacement Transducer (LVDT). The coefficient of friction, μ, is then calculated from the following formula:

$$\mu = F/N$$

F = dynamic friction force

N = Normal force (load)

b. At the end of the test, the ball has an elliptical wear pattern. The major and minor axes of the pattern are measured. The averaged value is the wear scar diameter, WSD. The WSD is the primary measurement of the Ball-on-Cylinder device.

c. The percent metallic contact between the Ball and Cylinder is measured by means of an electrical resistance. At loads in excess of 240 gms, the percent metallic contact was always 100%. This indicates the device is operating in the boundary lubrication region. In this report, the percent metallic contact was always

100% and is not discussed further.

The metallurgy of the balls and cylinders is AISI-52100 steel. The ball has a hardness of 60-62 Rockwell C and a surface finish of 2 micro-inches CLA. The cylinder has a hardness of 22.5 Rockwell C and a surface finish from 6-10 micro-inches CLA. In the course of the program, it was found that a small change in the hardness of the cylinders would greatly affect the size of the final wear scar. For example, two hydrocarbons were tested under the following conditions: 1000 gm load, 240 rpm speed, .5 ft^3/in. in dry air, indirect purging, and 32 minute test. In the first case, the cylinder hardness was 26 Rockwell and, in the second case, the hardness was 22.5 Rockwell C. The wear scars in Case 1 were .91 for methylnapthalene and 1.13 for Indene. In the second case, the wear scars in the same order were .73 and .92. An increase in hardness of only 3.5 Rockwell C increased the size of the wear scars 24.7% for methylnapthalene and 22.8% for Indene. The hardness of the cylinders is critical and must be held within 1 Rockwell C between two devices if a one-on-one repeatability and reproducibility is sought.

3.2 Bendix-CRC Lubricity Simulator

Basically, as illustrated in Figure 3, the simulator consists of two sets of spools in contact with two sleeves. The spools and sleeves are made from an anodized aluminum. The contact surface finish areas are approximately 10 rms and the clearances between the spool and sleeve are from .3 to .5 mils. The sleeves are held stationary by the test block, and the spools are connected to a reciprocating drive system. A load ring is located between each spool and the drive

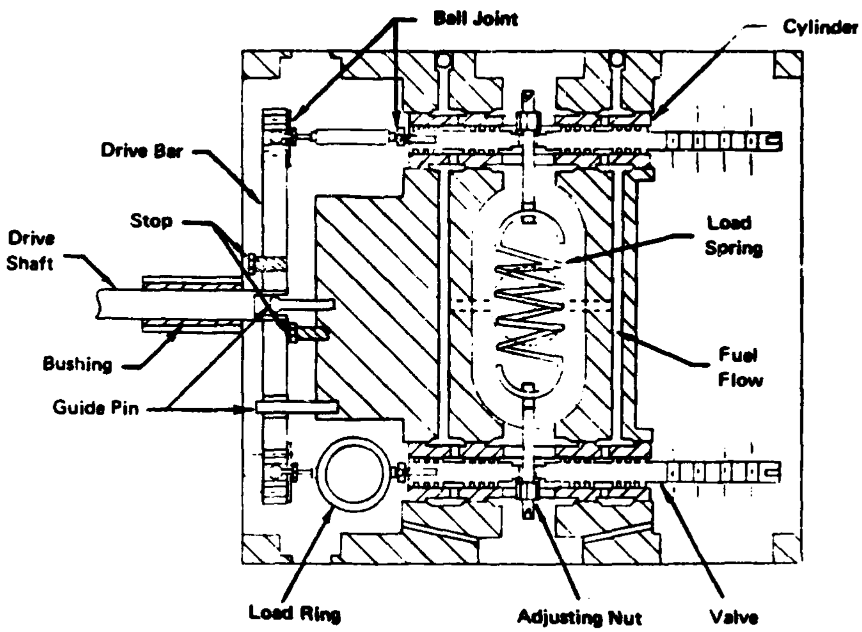

Figure 3. Bendix - CRC Lubricity Simulutor Schematic

system. A perpendicular side load is applied to each spool by a spring. During operation, the test fuel is supplied to the spools bv a nitrogen pressurized feed system. The normal operating conditions of the device are 3.0 ml/min. flow rate of fuel, 5 pound side load, and .26 inch spool travel at a frequency of 10 cycles/min[4]. During the rigs operation, the spool slides in the sleeve and a friction force results. The friction force is measured by the load ring and recorded on a strip recorder. It is also possible to record the friction force versus position of the spool in the sleeve by a linear variable differential transducer attachment on the spool. The maximum force normally occurs durinq the beginning or end of one stroke (1/2 cycle). Therefore, the maximum force corresponds to the static friction force.

From the load ring frame of reference, there is a tension and compression stroke for one complete cycle. The test is terminated when the static friction force reaches equilibrium, which may vary from 4 to 9 hours. The coefficient of static friction is calculated by dividing the average of the equilibrium static friction forces from the tension and compression stroke by the side load.

4.0 Repeatability of Ball-on-Cylinder

In earlier work by the Air Force, the repeatability of the Ball-on-Cylinder device was very poor. The wear scar diameter would vary in excess of 20% for the same fluid at identical operating conditions. The poor repeatability was attributed to two major causes: (1) an uncontrolled environment at the point of contact between the ball and cylinder and (2) irregular surface finishes on the cylinders. These items have been corrected and the current operating conditions were discussed in Section 3.1. It was not known if the repeatability of the Ball-on-Cylinder also varied due to the number of constituents in the test fluid. In order to determine this, pure hydrocarbons and Jet A-1 fuels were tested on the rig.

4.1 Pure Hydrocarbons

The results are listed in Tables 2 and 3 for the hydrocarbons. The WSD ranged from .26 mm to .92 mm whereas the coefficient of friction changed only from .04 to .26. The repeatability of the WSD is defined as the maximum deviation from the mean wear scar diameter times 100 and divided by the mean wear scar diameter. The repeatability of the WSD for the seventeen hydrocarbons varied from 0.0% to 9.1% which is within experimental acceptability.

The hydrocarbons can be arranged into groups according to their coefficient of friction. It was found that for the group with the coefficient of friction of .19, the wear scar diameters varied by a maximum factor of 2.8. Similar results of hydrocarbons with the same coefficient of friction but vastly different wear scar diameters were reported by ESSO.[5]

4.2 Jet A-1 Fuels

The Ball-on-Cylinder results for the thirteen Jet A-1 fuels are shown in Table 4. The wear scar diameters ranged from .25 mm to .48 mm whereas the coefficient of friction varied from .11 to .14. This

TABLE 2

Repeatability and Reproducibility of Ball-on-Cylinder on Hydrocarbons (240 gm Load)

FLUID	AIR FORCE PURITY	AIR FORCE* WSD (mm)	REPEAT-ABILITY OF AF WSD (%)	ESSO** WSD (mm)	AF COEFF.* OF FRICT.	ESSO COEFF.** OF FRICTION	REPRODUC-ABILITY OF WSD (%)	AIR FORCE RANK	ESSO RANK
Bicyclo (2,2,1) Heptadi (2,5)ene	Practical	.51	3.9	.40	.19	.19	21.6	11.0	7.0
Benzene	Practical	.46	4.3	.52	.26	.19	13.0	10.0	13.5
Cetane	Reagent	.26	7.7	.24	.11	.14	7.7	1.5	1.0
Cyclohexane	Reagent	.73	3.1	.74	.19	.20	1.4	15.5	16.0
Cyclohexene	Practical	.26	6.5	.31	.19	.23	19.2	1.5	4.0
Dodecane	99 + %	.40	9.1	.39	.12	.14	2.5	6.5	6.0
Hexane	99 + %	.56	1.2	.62	.23	.22	10.7	14.0	15.0
Octane	99 + %	.45	4.4	.45	.15	.19	0.0	9.0	10.0
Octene-1	Practical	.28	.0	.33	.16	.18	17.9	3.0	5.0
Toluene	99 + %	.53	7.5	.49	.19	.16	7.6	13.0	11.0

* Mean of five trials. Operating conditions: 240 rpm, 75°F, .5 ft^3/min, indirect flowrate of dry air, AISI 52100 Steel test specimens (ball, 60 - 63 Rockwell C and cylinder, 22.5 Rockwell C), and 32 min test time.

** Data from reference 5.

TABLE 3

Repeatability and Reproducibility of Ball-on-Cylinder on Hydrocarbons (1000 gm Load)

FLUID	AIR FORCE PURITY	AIR FORCE* WSD (mm)	REPEAT-ABILITY OF AF WSD (%)	ESSO*** WSD (mm)	AF COEFF.* OF FRICT.	ESSO COEFF.*** OF FRICTION	REPRODUC-ABILITY OF WSD (%)	AIR FORCE RANK	ESSO RANK
Decalin	Practical	.52	5.8	.50**	.11	.14	3.8	12.0	12.0
Diphenyl-Methane	Practical	.38	5.3	.43	.14	.12	13.2	5.0	9.0
Indene	Practical	.92	5.4	.90**	.04	.15	2.2	17.0	17.0
Methyl-Naphthalene	Practical	.73	4.0	.52**	.10	.11	28.8	15.5	13.5
α-Methylstyrene	Reagent	.41	7.3	.28	.10	.14	31.7	8.0	3.0
Ar-Methylstyrene	Technical	.34	4.4	.25	.10	.11	26.5	4.0	2.0
Tetralin	Practical	.40	2.5	.42	.10	.16	5.0	6.5	8.0

* Mean of five trials. Operating conditions: 1000 gm load, 240 rpm, 75°F, .5 ft^3/min indirect flowrate of dry air, AISI 52100 Steel test specimens (ball, 60 - 63 Rockwell C and cylinder, 22.5 Rockwell C) and 32 min test time.

** Rerun by ESSO

*** Data from reference 5.

TABLE 4

Repeatability and Reproducibility of Ball-on-Cylinder on Jet A-1 Fuels Under Similar Test Conditions

JET A-1 FUEL	AIR FORCE* WSD (mm)	REPEAT-ABILITY OF AF WSD (%)	AF COEFF.* OF FRICT.	ESSO WSD (mm)	REPRODUC-ABILITY OF WSD (%)	AIR FORCE RANK	ESSO RANK
171-1	.49	5.1	.13	.40	18.4	13.0	10.5
171-2	.26	0.0	.14	.24	7.7	2.0	1.5
171-3	.47	6.4	.12	.35	25.5	10.0	8.0
171-5	.46	4.4	.12	.40	13.0	9.0	10.5
271-1	.48	8.7	.12	.41	14.6	11.5	12.0
271-3	.45	6.6	.12	.38	15.5	8.0	9.0
371-1	.38	6.6	.12	.28	26.3	6.5	6.0
371-2	.38	2.6	.13	.30	21.1	6.5	7.0
471-1	.48	1.1	.13	.44	8.3	11.5	13.0
970-1	.28	8.4	.12	.27	3.6	5.0	5.0
970-2	.27	3.7	.11	.25	7.4	3.5	3.5
970-3	.25	0.0	.14	.25	0.0	1.0	3.5
1170-2	.27	5.4	.11	.24	11.1	3.5	1.5

* Mean of three trials. Operating conditions: 1000gm loads 240rpm, 75°F, .5ft^3/min., indirect flowrate of dry air, AISI 52100 steel test specimens (ball, 60-63 Rockwell C and cylinder, 22.5 Rockwell C), and 32 min. test time.

also illustrates that the WSD is more sensitive to the lubricity of fuels than the coefficient of friction. The repeatability of the WSD is from 0.0% to 8.4% which is also acceptable. These results show that the repeatability of the WSD from the Ball-on-Cylinder is not influenced by the complexity of the test fluid.

5.0 Reproducibility of Ball-on-Cylinder

As in the case of the rig's repeatability, the reproducibiltty of the device was examined on both pure hydrocarbons and fuels. The purity of the pure hydrocarbons were matched as close as possible with those tested by ESSO between 1966-67 on Contract AF33(615)-2828. The fuels were 13 Jet A-1s from the World Fuel Survey and part of an ASCC Lubricity Program, TPA Nr 647-15. They were tested by ESSO Research and Engineering, New Jersey, as part of a joint program with the Air Force.

5.1 Pure Hydrocarbons

The reproducibility of the wear scar diameters for each hydrocarbon are listed in Tables 2 and 3. It varied from 0.0% to 46.4%. This is quite large and any test device with such a poor reproducibility is subject to skepticism.

The wear scar diameters obtained from the Air Force and ESSO on the hydrocarbons were tested for independence with the Spearman Rank Correlation Coefficient Statistic[6]. In this statistic, the rank correlation coefficient, r, is calculated by the following formula:

$$r = 1 - \frac{6\Sigma D^2}{N\,(N-1)}$$

D = Difference between ranks of corresponding values of x and y

N = Number of pairs of values (x,y) in the data

The value of r may range from -1 to +1. The hypothesis test for the Spearman Statistic is based on the rank correlation coefficient. The null hypothesis is:

H_0: r = o   x and y are independent

The alternate hypothesis is:

H_i: r > o   x and y are dependent (one sided test)

The null hypothesis is rejected if $r \geq K(\alpha, n)$ where r is the rank coefficient, and the constant $K(\alpha, n)$ satisfied $P_0 \{r \geq K(\alpha,n)\} = \alpha$ which is the probability that $r \geq K(\alpha, n)$. The level of significance of the test is equal to α which is the probability of rejecting H_0 when it is true, and the number of data points is equal to n. The null hypothesis is accepted if $r < K(\alpha,n)$.

If $K(\alpha,n)$ is set equal to r, an approximate value of α may be obtained from tabulated statistical tables of n, α, and $K(\alpha,n)$ since n is known. It is the author's opinion that x and y are dependent if the calculated rank coefficient has a level of significance less than or equal to 5%.

The calculated rank coefficient for the relation between wear scar diameters obtained in the hydrocarbon study was .881, which indicates they correlate with a level of significance less than .5%,; i.e., the wear scar diameters appear to be dependent. A linear least squares regression was also performed on the wear scar diameters. The regression line and standard error of estimate, 0.071, are shown in Figure 4. This analysis indicates a correlation does exist between the Ball-on-

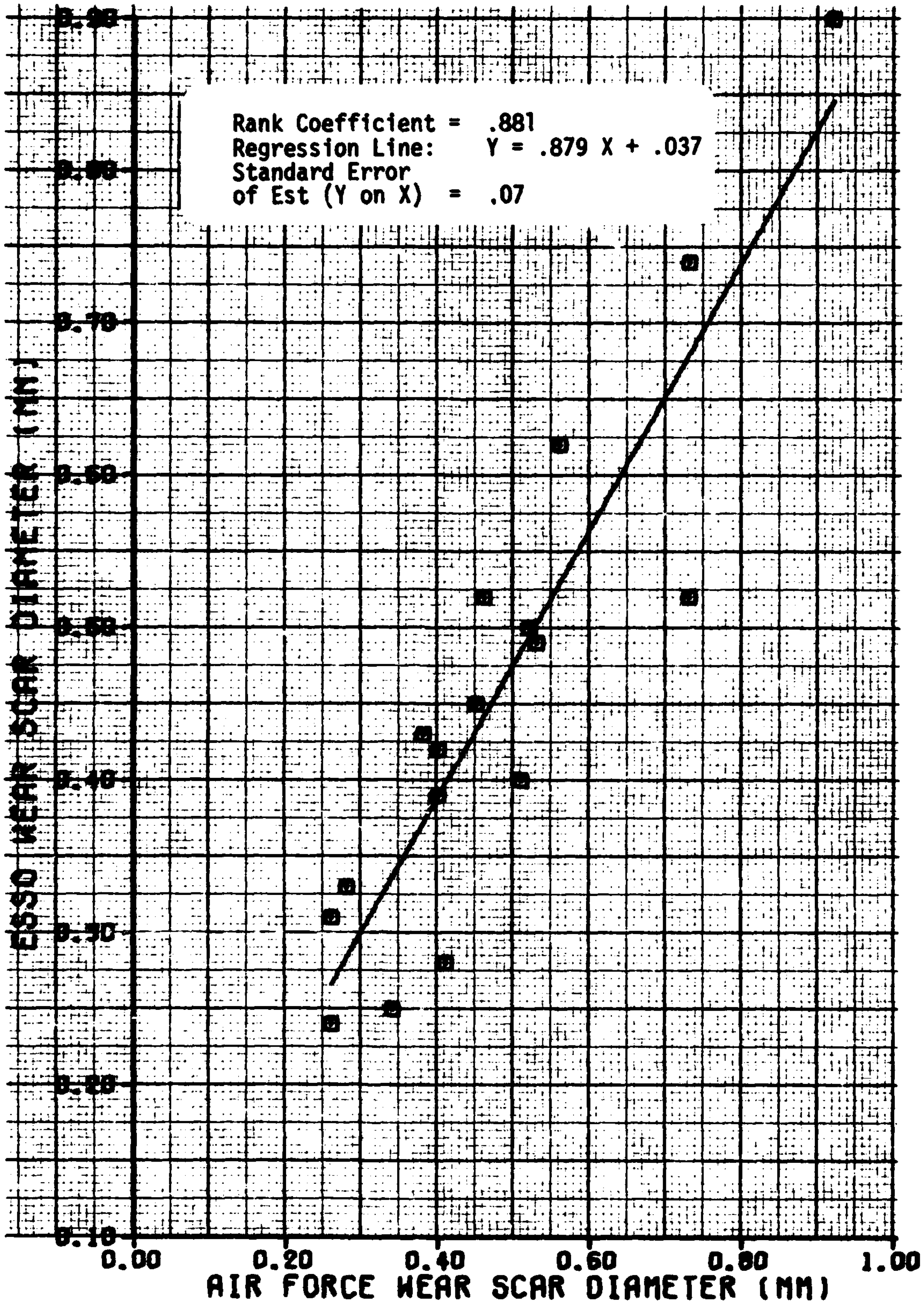

Figure 4. Hydrocarbon Study: Ball-on-Cylinder

Cylinder rigs operated by the Air Force and ESSO. For a perfect correlation, the regression equation would be Y = X. However, there are several factors which would cause the correlation to deviate from ideal. In this case, it is believed the wear scars were more sensitive to the hydrocarbons' chemical purity than originally suspected. Decaline, Indene, and methylnapthalene were originally severely out of line in the correlation. The original ESSO literature results were wear scar diameters of .35, .72, and .33. Conversely, the Air Force wear scar diameters were .52, .92, and .73. ESSO tested the Air Force's three samples of the above hydrocarbons and obtained wear scar diameters of .50, .90, and .52. Therefore, it is likely that the overall correlation between the two laboratories Ball-on-Cylinder rigs established on the hydrocarbons may be influenced by the difference in purity of other hydrocarbons besides the three previously mentioned. This could have, in turn, affected the rigs reproducibility.

Other factors which could cause the correlation to vary from ideal are differences in the metallurgy of the test specimens (discussed in Section 3.1), operating conditions, or operating procedures.

5.2 Jet A-1 Fuels

The Jet A-1 fuels were tested by ESSO and the Air Force under similar conditions on the Ball-on-Cylinder rigs with one exception. The Air Force purged the test cell by the indirect flow method whereas ESSO purged the test cell by a combination of the direct and indirect method. These two sets of data are compared in Table 4.

The reproducibility of the wear scar diameters varied from 0.0% to 26.3%. This is a large improvement over the 0.0 to 46.4%

reproducibility determined in the pure hydrocarbon study, but it is still quite large. The improvement in reproducibility is attributed to both laboratories testing the same samples of fuel instead of similar batches as in the case of the pure hydrocarbons.

A statistical analysis was also performed on the wear scar diameters for each fuel from both laboratories. The rank coefficient was .926 which corresponds to a level of significance less than .1%. This indicates the wear scar diameters between laboratories are dependent. The linear regression line of y on x and the standard error of estimate for the relation between the laboratories WSD for the Jet A-1 fuels data are plotted in Figure 5. The standard error of estimate has decreased from .07 for the pure hydrocarbon study to .02 for the Jet A-1 study. This indicates that the correlation between wear scar diameters in the hydrocarbon study was influenced by differences in purities of the hydrocarbons tested.

The same set of Jet A-1 fuels were rerun by the Air Force using the identical test cell purging conditions employed by ESSO. The measured WSD's and their corresponding correlation with the ESSO data are tabulated in Table 5. The reproducibility of the wear scar diameters under the identical test conditions ranged from 0.0 to 19.1%; however, only five of the thirteen fuels were over 10% (171-3, 10.2%, 271-3, 1 .1%; 371-1, 15.1%; 920-1, 12.9%; and 970-2, 13.6%) and only 271-1 and 371-1 are over 14%. Although this reproducibility is an improvement over the one established for the previous study under similar test conditions, it is in a gray area as far as experimental acceptability is concerned. Ideally, the reproducibility of a device should be less than 10%.

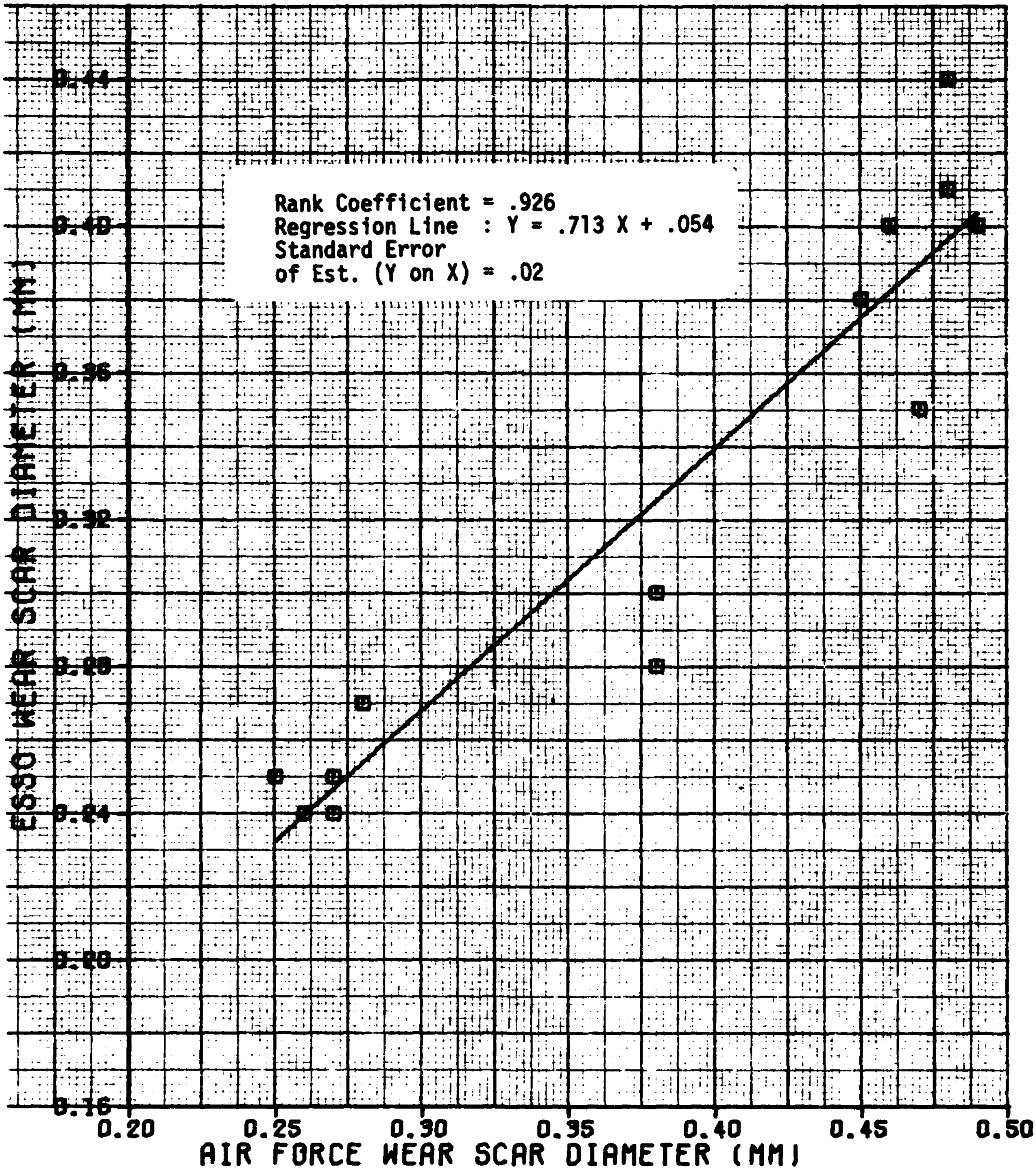

Figure 5. Jet A-1 Study under Similar Test Conditions: Ball-on-Cylinder

TABLE 5

REPRODUCIBILITY OF BALL-ON-CYLINDER ON JET A-1 FUELS UNDER EXACT TEST CONDITIONS

JET A-1 FUELS	AIR FORCE* WSD (mm)	REPRODUCABILITY OF WSD (%)	AIR FORCE* COEFFICIENT OF FRICTION	AIR FORCE RANK
171-1	.44	9.1	.15	11.5
171-2	.24	0.0	.15	3.0
171-3	.39	10.2	.17	11.0
171-5	.37	8.1	.17	9.0
271-1	.38	7.9	.18	10.0
271-3	.47	19.1	.17	13.0
371-1	.33	15.1	.16	7.0
371-2	.29	3.4	.17	5.0
471-1	.48	8.3	.15	11.5
970-1	.31	12.9	.15	6.0
970-2	.22	13.6	.16	1.0
970-3	.23	8.7	.15	2.0
1170-2	.26	7.7	.18	4.0

* Mean of 3 trials. Operating Conditions: 1000 gm load, 240 rpm, 75°F, .5 ft^3/min Indirect flowrate of dry air, AISI 52100 steel test specimens (ball, 60-63 Rockwell C and cylinder, 22.5 Rockwell C), and 32 min test time.

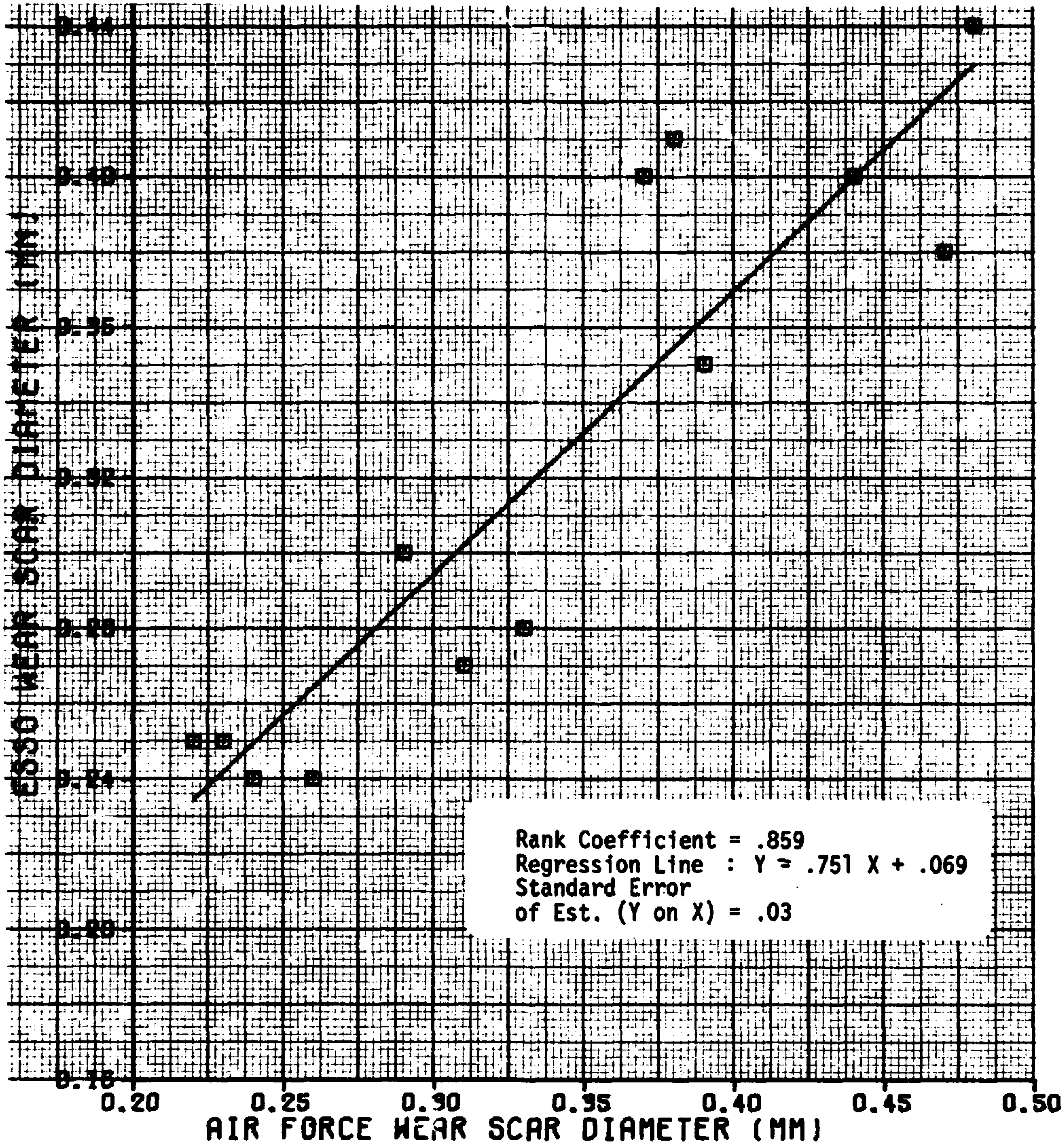

Figure 6. Jet A-1 Study under Exact Test Conditions: Ball-on-Cylinder

The same statistical analysis was applied to the Air Force wear scar diameters and ESSO's. The rank coefficient was .859 which corresponds to a level of significance less than .1%. This indicates the wear scar diameters are still dependent for the Jet A-1 fuels, at the .1% level. The regression line and standard error of estimate are plotted in Figure 6. It can be seen that the standard error of estimate has risen to .03; however, the statistical analysis has not changed significantly, and it still confirms that the WSDs are dependent.

6.0 Correlation Between Ball-on-Cylinder and Bendix-CRC Lubricity Simulator

The Bendix-CRC Lubricity Simulator was designed to simulate the fuel control components affected by the fuel lubricity problem in 1965. As discussed in the "Background", (Section 1.0), the Ball-on-Cylinder actually distinguished between a fuel which caused service lubricity problems and two that did not. Therefore, a possible correlation between the two rigs was examined. The 13 Jet A-1 Fuels discussed in the previous section were also tested by General Electric using their Bendix-CRC Lubricity, and the General Electric data was used in this correlation.

The test devices have two significant differences between them:

a. The measured lubricity parameter is the wear scar diameter for the Ball-on-Cylinder device and is the static friction force for the Lubricity Simulator.

b. The metallurgy of the test specimens is steel for the Ball-on-Cylinder and aluminum for the Lubricity Simulator.

The Air Force derived Ball-on-Cylinder's wear scar diameter and the General Electric derived Bendix-CRC Lubricity Simulator's coefficient of friction for each fuel were tested for independence with the Spearman Rank Statistic. The rank coefficient was .731 which corresponds to a level of significance less than .5%. Thus, the wear scar diameters and coefficient of friction appear to be dependent. A linear regression analysis was also performed on the relation between the coefficient of friction from the simulator and the wear scar

diameters from the Ball-on-Cylinder. The regression line and standard error of estimate are shown in Figure 7 for this relation. Based on the regression line, the wear scars are more sensitive to the fuel than the corresponding coefficients of friction. An increase in wear scar diameter of 33% from the original value of .40 mm corresponds to an increase in coefficient of friction of only 17.4%.

This correlation between test rigs on the Jet A-1 fuels leads to two major conclusions:

a. Either the friction (lubricity simulator) or wear (Ball-on-Cylinder) type of lubricity test rig can be used. The important considerations are that they operate in the boundary lubrication region and that all the environmental parameters are controlled.

b. The metallurgy of the test specimens in a lubrictty rig is not a major factor in the ranking of fuels by their lubricity. In some cases, there may be consttituents of the fuel which are sensitive to the metallurgy, but this is not a general trend.

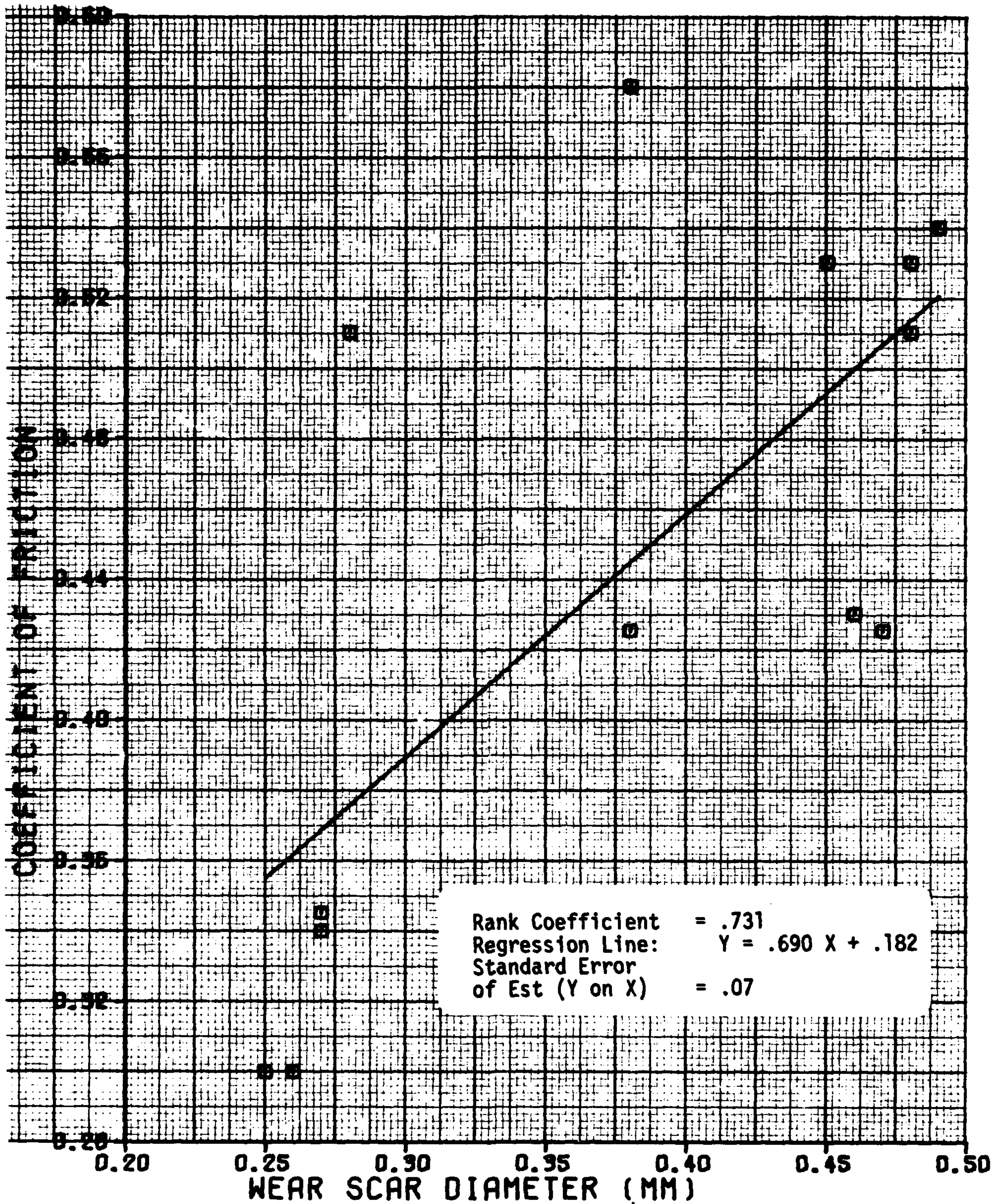

Figure 7. Lubricity Simulator: Ball-on-Cylinder Correlation

7.0 CORRELATION BETWEEN WSD FROM BALL-ON-CYLINDER AND PHYSICAL PROPERTIES OF FUELS

The combustion characteristics of a fuel are controlled by requirements on its physical properties. There are currently many specification requirements associated with a fuel. A question which arises is: can the lubricity of a fuel be controlled by more stringent limits on one or more existing properties? In an effort to further investigate this idea, a correlation between each physical property and wear scar diameter from the Ball-on-Cylinder for a series of fuels was examined. The fuels were Jet A-1's and JP-4's.

7.1 Jet A-1 Fuels

The physical properties of the Jet A-1 fuels discussed in Section 4.2 are tabulated in Table 6. The physical properties of each fuel and its wear scar diameter were tested for independence using the Spearman Rank Statistic. In this case, a two sided test was used where the null hypothesis, H_o, is that the x and y's are independent.

$$H_o = r = o \quad \text{independent x and y's}$$

$$H_i = r \neq o \quad \text{dependent x and y's}$$

H_o is rejected if $r \geq K(\alpha_2, n)$ or $r \leq -K(\alpha_1, n)$ where α_2 and α_1 are the upper and lower probabilities, respectively.

$$P_o\{r \geq K(\alpha_2, n)\} = \alpha_2 \qquad P_o\{r \leq K(\alpha_1, n)\} = \alpha_1$$

The level of significance, α, is equal to $\alpha_1 + \alpha_2$ and is the probability of rejecting H_o when it is indeed true. The hypothesis,

TABLE 6

PHYSICAL PROPERTIES OF JET A-1 SURVEY FUELS

METHOD	PROPERTY	SPEC. LIMIT	171-1	171-2	171-3	171-5	271-1	271-3	371-1	371-2	471-1	870-3	970-1	970-2	970-3	970-4	1070-1	1170-2
	COMPOSITION																	
D1319	Aromatics (Vol %)	20.	20.2	15.5	14.6	17.5	17.2	17.5	16.6	18.3	13.8	13.6	15.6	18.5	17.9	16.0	19.2	17.3
D1319	Olefins (Vol %)		1.0	0.6	0.7	0.8	1.3	1.3	1.3	1.3	1.2	1.0	1.1	1.6	1.2	0.6	1.0	1.0
D.219	Sulfur, Mercaptan (Wt %)	0.003	-	-	-	-	-	-	-	-	-	-	-	-	0.002	-	-	-
D.84	Doctor Test (P=Pos, N=Neg)		N	N	N	N	N	N	N	N	N	N	N	N	P	N	N	N
D.1260	Sulfur, Total (Wt %)	0.3	0.0	0.06	0.07	0.01	0.03	0.08	0.11	0.04	0.02	0.14	0.07	0.17	0.09	0.0	0.02	0.05
	Basic Nitrogen (ppm) [1]		0.4	-	-	-	0.7	0.2	1.5	-	-	-	2.8	5.8	-	0.0	0.9	2.6
	Carbon (Wt %) [2]		86.05	85.94	85.74	86.21	85.73	85.96	85.90	85.96	86.04	85.77	86.12	86.20	86.44	85.97	85.98	86.03
	Hydrogen (Wt %) [2]		13.97	14.06	14.26	13.65	14.36	14.05	13.99	14.02	13.95	14.22	13.70	13.81	13.58	14.03	13.96	13.94
	VOLATILITY																	
D86	Distillation Init. BP (°F)		314	320	316	332	317	313	310	338	316	336	316	326	316	319	341	330
	10% Rec (°F)	400	335	342	342	350	350	337	343	353	342	368	350	358	356	361	378	350
	20% Rec (°F)		344	350	352	358	360	346	357	358	352	378	363	371	373	371	391	360
	50% Rec (°F)	450	373	373	375	381	386	370	386	372	374	410	398	406	412	396	424	388
	90% Rec (°F)		444	440	428	438	438	[illegible]	450	414	427	469	474	481	482	438	492	450
	95% Rec (°F)		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Final BP (°F)	550	480	487	459	471	478	480	488	448	470	504	510	524	526	488	531	501
	Residue (%)	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Loss (%)	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
D56	Flashpoint (°F)	110-150	-	114	114	128	116	110	112	128	112	128	116	120	118	118	134	120
D287	Gravity, API (60°F)	39-51	48.1	46.6	47.9	46.2	47.0	50.0	47.0	47.6	48.2	42.0	43.3	42.3	39.6	45.4	41.5	45.0
D1298	Gravity, Specific (60/60°F)		.788	.794	.789	.796	.793	.780	.793	.790	.787	.816	.809	.814	.827	.800	.818	.802
	FLUIDITY																	
D2386	Freezing Point (°F)	-54	-65	-67	-69	-68	-64	-76	-66	-77	-65	-70	-60	-70	<-90	-77	-71	-71
D445	Viscosity @ -30°F (cst)	15	5.0	5.5	5.3	6.0	6.0	5.1	6.0	5.3	5.4	9.3	7.3	8.5	9.6	6.9	11.1	6.6
	@ +32°F (cst)		2.1	2.2	2.2	2.4	2.4	2.1	2.4	2.2	2.2	3.1	2.7	2.9	3.2	2.6	3.5	2.5
	@ 100°F (cst)		1.1	1.2	1.2	1.2	1.2	1.1	1.3	1.2	1.2	1.5	1.4	1.5	1.6	1.3	1.6	1.3
	COMBUSTION																	
D1405	Aniline-Gravity Product		6806	6664	7017	6653	6839	7150	6909	5985	7134	6195	6149	5964	5405	6628	6059	6638
D1405	Net Heat of Combustion (Btu/lb) [3]	18400	18661	18639	18675	18645	18662	18689	18658	18567	18695	18576	18581	18547	18496	18643	18578	18637
D240	Net Heat of Combustion (Btu/lb) [4]		18692	18608	18642	18694	18606	18660	18621	18650	18672	18500	18631	18511	18514	18614	18544	18569
D240	Gross Heat of Combustion (Btu/lb) [5]		19962	19891	19943	19939	19916	19942	19897	19930	19945	19797	19890	19771	19753	19894	19818	19841
D611	Aniline Point (°F)		141.5	143.0	146.5	144.0	145.5	143.0	147.0	142.5	148.0	147.5	142.0	141.0	136.5	146.0	146.0	147.5
D1740	Luminometer No.	45	55	57	58	53	58	57	58	55	65	52	50	44	41	51	45	50
D1322	Smoke Point	20-25	23.0	21.0	22.0	20.0	20.0	20.0	20.0	19.0	20.0	19.0	19.0	18.0	18.0	19.0	18.0	18.0
	CONTAMINANTS																	
D381	Existent Gum (mg/100ml)		0.2	0.6	0.2	0.0	0.4	0.6	0.6	0.2	-	-	-	6.6	11.2	0.0	1.2	0.2

1 Universal Oil Products Method 313-58
2 Averaged Values
3 Calculated from equations in ASTM D1405
4 Calculated using equation: Heat of Combustion = Gross Heat, Btu/lb - 91.23 x % Hydrogen
5 Average value corrected for sulfur content

H_0, is accepted if $-K(\alpha_1, n) < r < K(\alpha_2, n)$. The values of $K(\alpha_2, n)$ and $K(\alpha_1, n)$ depend on the sample size, n, and the upper and lower level of significances, respectively. It is the author's opinion that the total level of significance should not be greater than 5% for the rejection of H_0. For 13 data points and a 5% level of significance, $-K(\alpha_1, n) = -.553$ and $K(\alpha_2, n) = .553$. The rank coefficients for Jet A-1 fuels are listed in Table 7, along with the standard error of estimates of y.

There are several physical properties of a fuel which have been thought in the past to be related to its lubricity. One such property is the sulfur content of a fuel. From Table 7, the rank coefficient for the relation between sulphur content and WSD for the Jet A-1 fuels was -.632 which indicates that sulphur content and WSD are related. However, the validity of this decision, based on the rank coefficient, is questionable once the data is more closely examined. The relation between sulfur content and WSD is shown in Figure 8 along with its regression line. As can be seen in this figure, the wt. % sulphur of the fuels ranged from .00% to .11% and several of the fuels were within .01% sulfur of one another. The reproducibility of the total sulfur test is approximately .01 wt %. Therefore, the fuels which are within .01 wt % sulfur of one another could possibly be in the wrong order. This would, in turn, affect the rank correlation. The decision as to whether or not the sulfur content is independent of WSD based on the rank coefficient is inconclusive because of the reproducibility of the sulfur test.

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TABLE 7

Physical Property - WSD Rank Correlation Coefficients
for
Jet A-1 Fuels

PHYSICAL PROPERTY	STANDARD ERROR OF ESTIMATE FOR Y	RANK COEFFICIENT
Aromatics	1.66	.085
Olefins	.270	.003
Sulfur Total	.030	-.632
Carbon Wt %	.16	-.298
Hydrogen Wt %	.19	.392
D86 - Init. BP	7.96	-.247
D86 - 10% Rec	5.60	-.523
D86 - 20% Rec	6.43	-.523
D86 - 50% Rec	9.99	-.460
D86 - 90% Rec	1.49	-.596
D86 - Final BP	16.2	-.690
Flashpoint	5.4	-.245
Gravity, API	1.76	.750
Gravity, Spec	.008	-.739
Viscosity @ -30°F	.96	-.647
Viscosity @ 32°F	.23	-.577
Viscosity @ 100°F	.11	-.437
Aniline Gravity Product	363.8	.666
Net Heat of Comb*	40.0	.787
Gross Heat of Comb	37.1	.889
Aniline Point	2.78	.368
Luminometer Nr.	4.33	.646
Existent Gum	2.75	-.479
Breakpoint**	18.4	.519

* Culculated values from equations in ASTM D1405.

** JFTOT data from Reference 7.

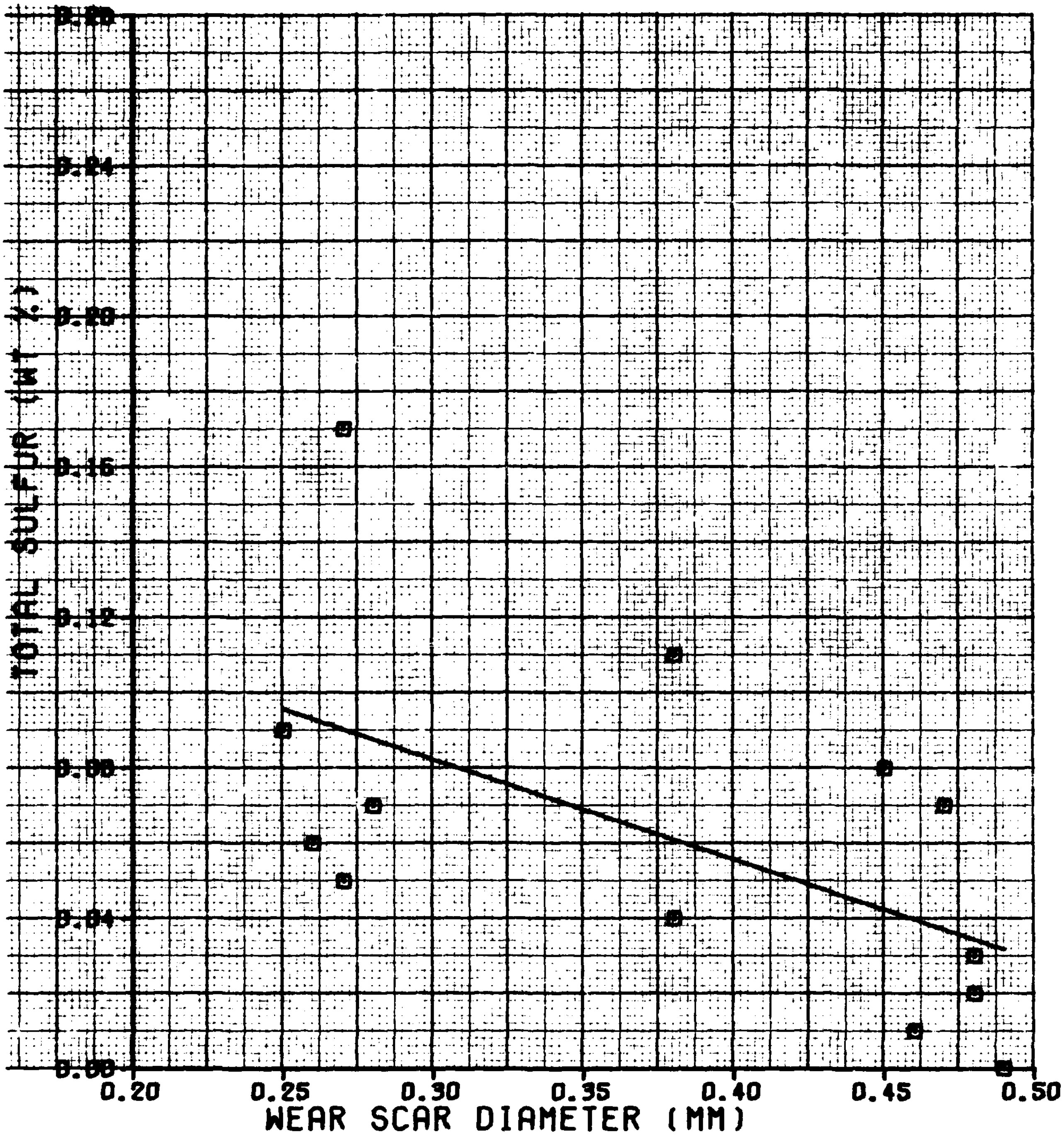

Figure 8. Total Sulfur vs WSD for Jet A-1 Fuels

The aromatic content of a fuel was also believed to be related to its lubricity. The aromatic content of the Jet A-1 fuels ranged from 13.67 to 20.2% and are plotted in Figure 9 vs WSD. The regression line is also shown on this figure. Since the rank coefficient, -.085, falls between -.553 and +.553, the null hypothesis, H_0, is accepted which states the aromatic content is independent of WSD at the 5% level of significance.

Another property of past interest is thermal stability. It is known that if a fuel's thermal stability has degraded, its stability can be restored by claytreating it. However, clay-treating will lower the fuel's lubricity. In general, it was the consensus that for a series of fuels, the fuels with the highest thermal stability would be the worst in lubricity. The regression line between thermal stability and WSD is plotted in Figure 10. The Spearman rank correlation from Table 7 for this relationship is .519 which also falls between -.553 and +.553. Therefore, WSD and thermal stability are independent at the 5% level of significance.

A number of physical properties not previously discussed in Table 7 have been found to correlate with the wear scar diameter from the Ball-on-Cylinder for the Jet A-1 fuels. They can be divided into two groups. Group A consists of the physical properties which correlated with the wear scar diameter and have negative rank coefficients which implies a negative slope for the regression line. The physical properties and their rank coefficients for Group A are:

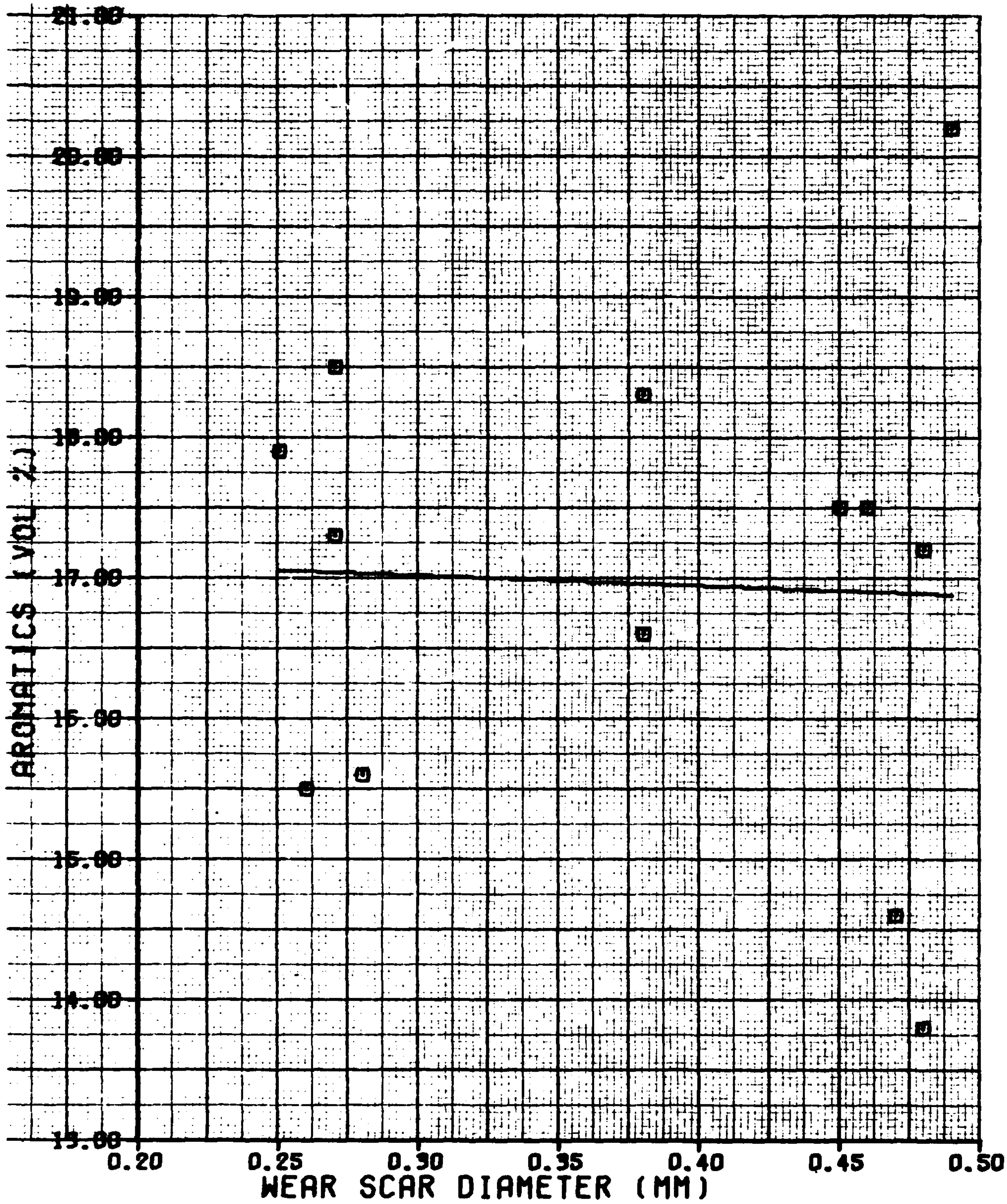

Figure 9. Aromatics vs WSD for Jet A-1 Fuels

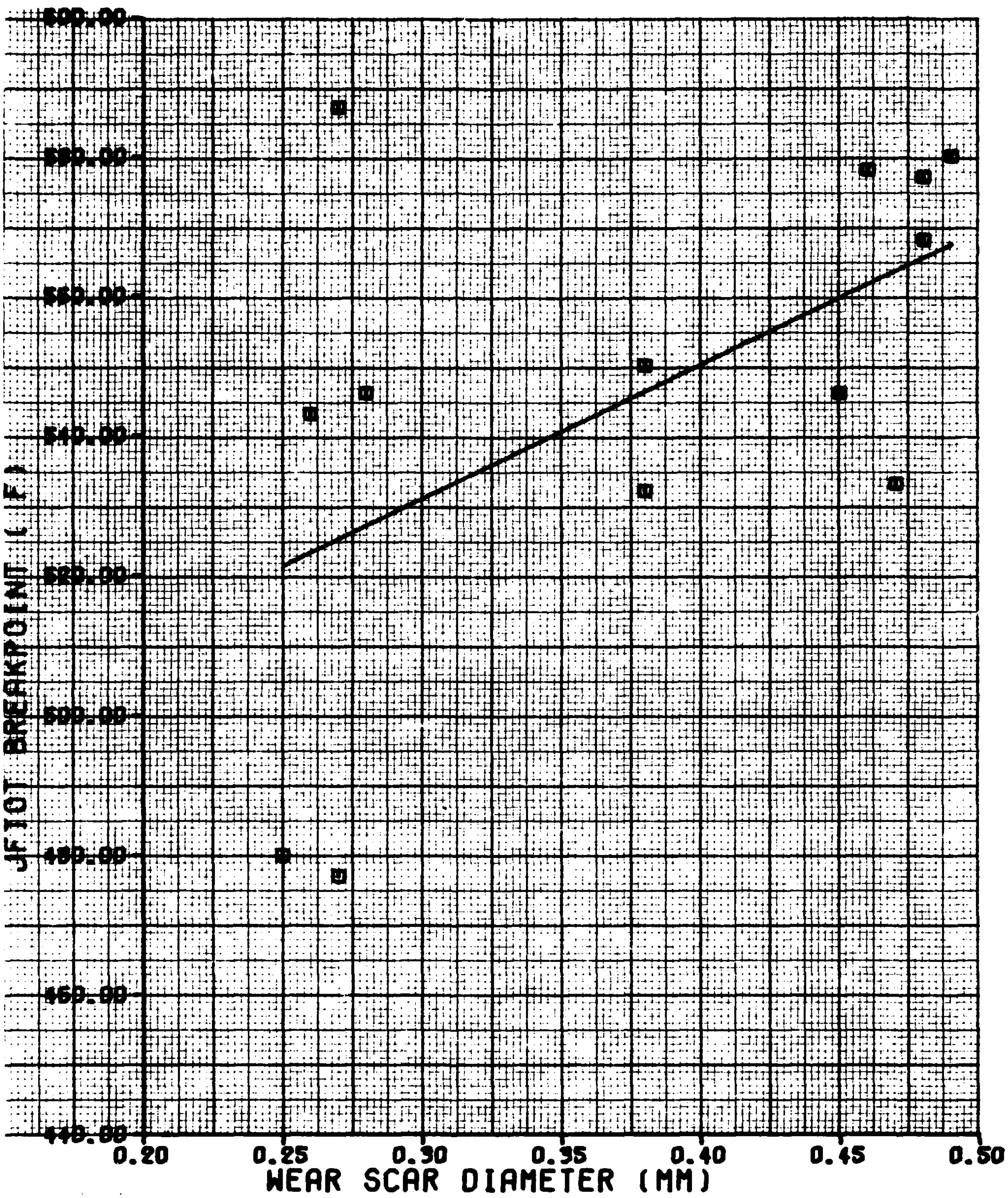

Figure 10. Thermal Stability vs WSD for Jet A-1 Fuels

D86 Distillation - 90% Recovery Temperature, -.590

Final Boiling Point, -.690

Viscosity @ -30°F -.647

Viscosity @ 32°F, -.577

Specific Gravity, -.739

The linear regression lines are shown in Figures 11 to 14 for the above correlations.

Group B consists of the physical properties which correlate with wear scar diameter and have a positive rank coefficient which implies a positive slope for the regression line. The physical properties of Group B and their rank coefficients are:

API Gravity, .750

Aniline Gravity Product, .666

Luminometer Number, .646

Net Heat of Combustion, .787

Gross Heat of Combustion, .889

The regression lines for Group B are shown in Figures 15 to 19.

The physical properties in Group A can be shown to be related to one common factor. The 90% Recovery B.P. is an indication of the amount of heavy ends in the fuel. The property can be interpreted to mean that 10% of the fuel components have boiling points equal to or greater than the 90% Recovery Boiling Point. For a homologous series, an increase in molecular weight will increase its boiling point. Therefore, a fuel which has a high 90% recovery B.P. will have higher

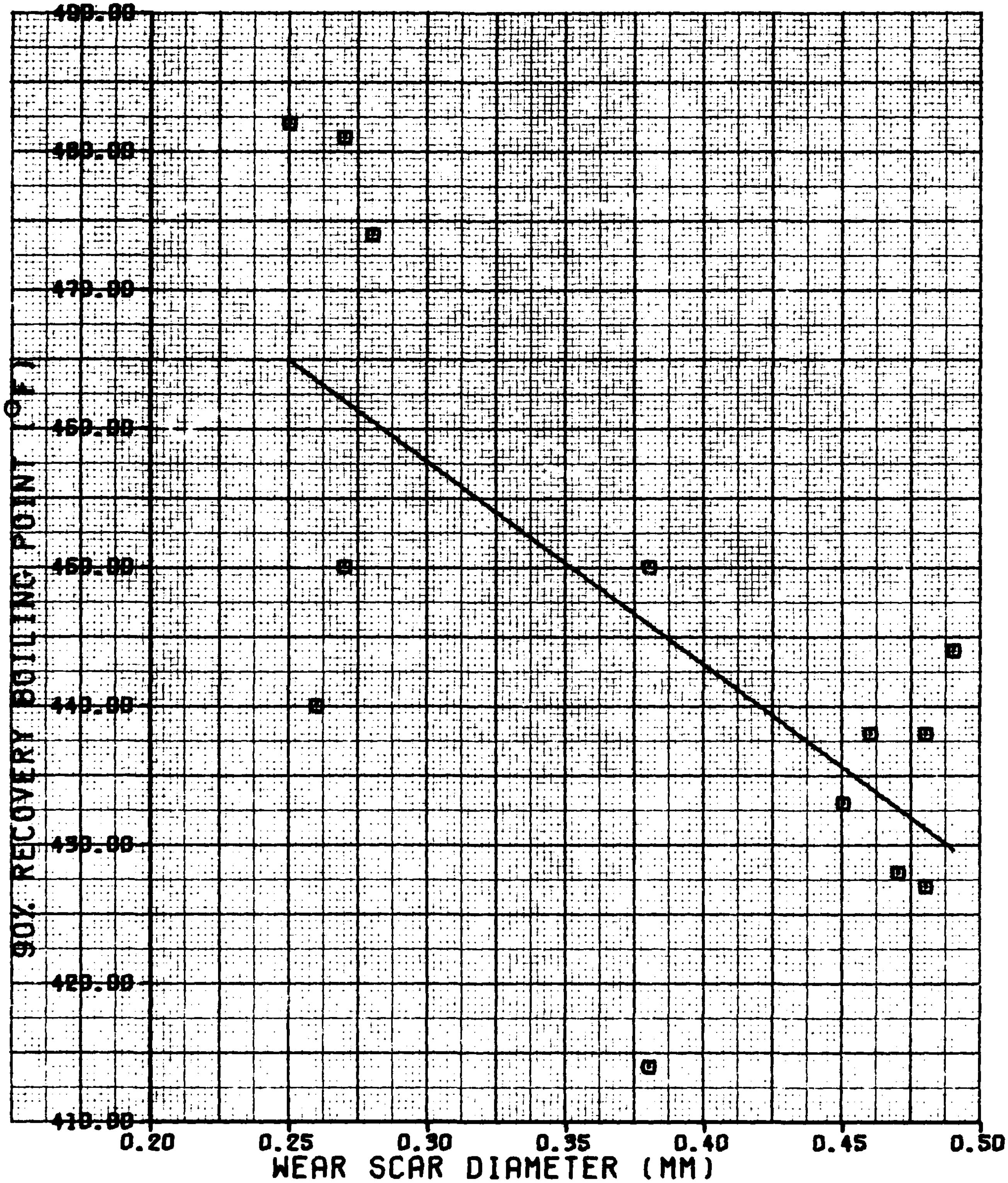

Figure 11. 90% Recovery Boiling Point vs WSD for Jet A-1 Fuels

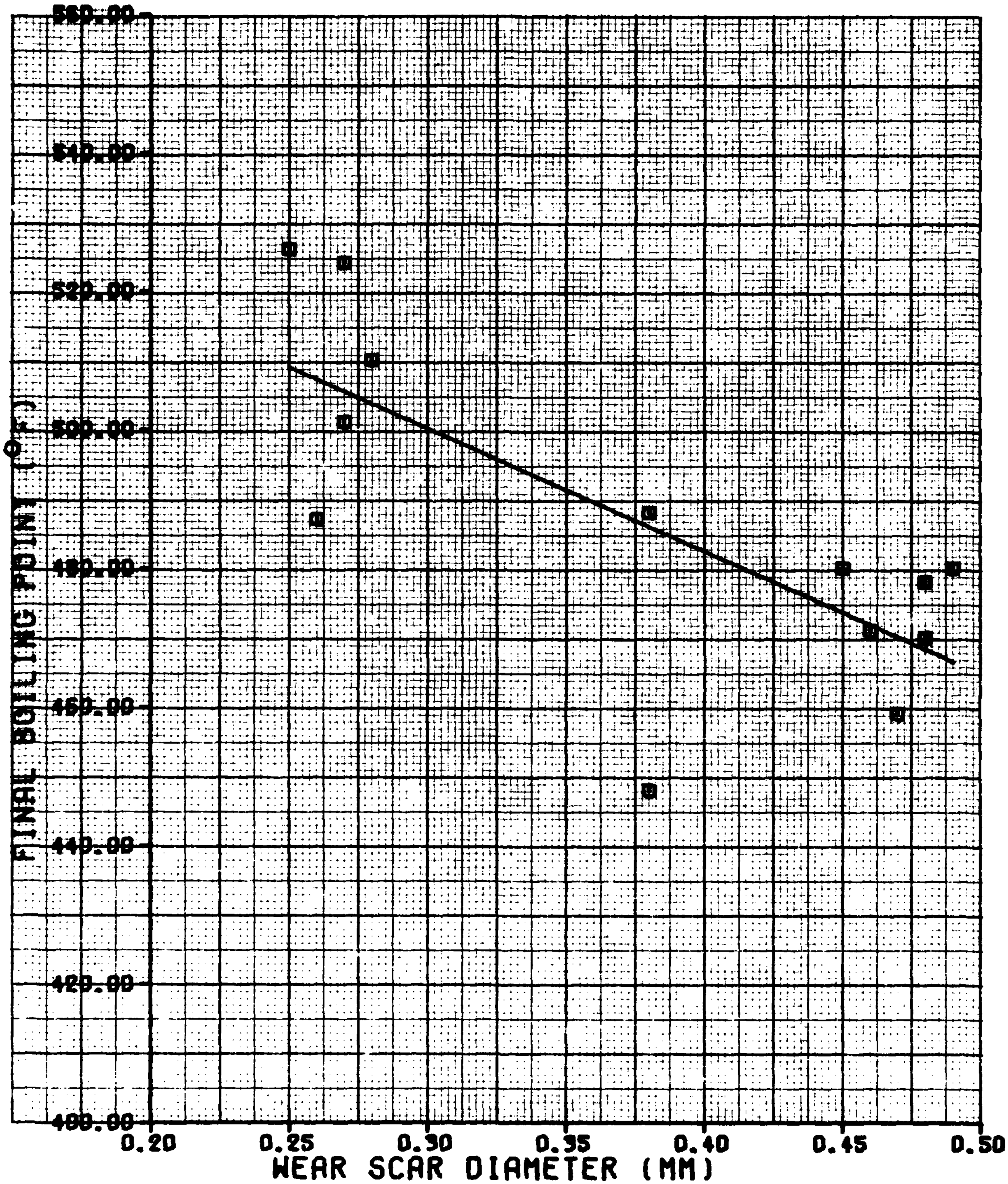

Figure 12. Final Boiling Point vs WSD for Jet A-1 Fuels

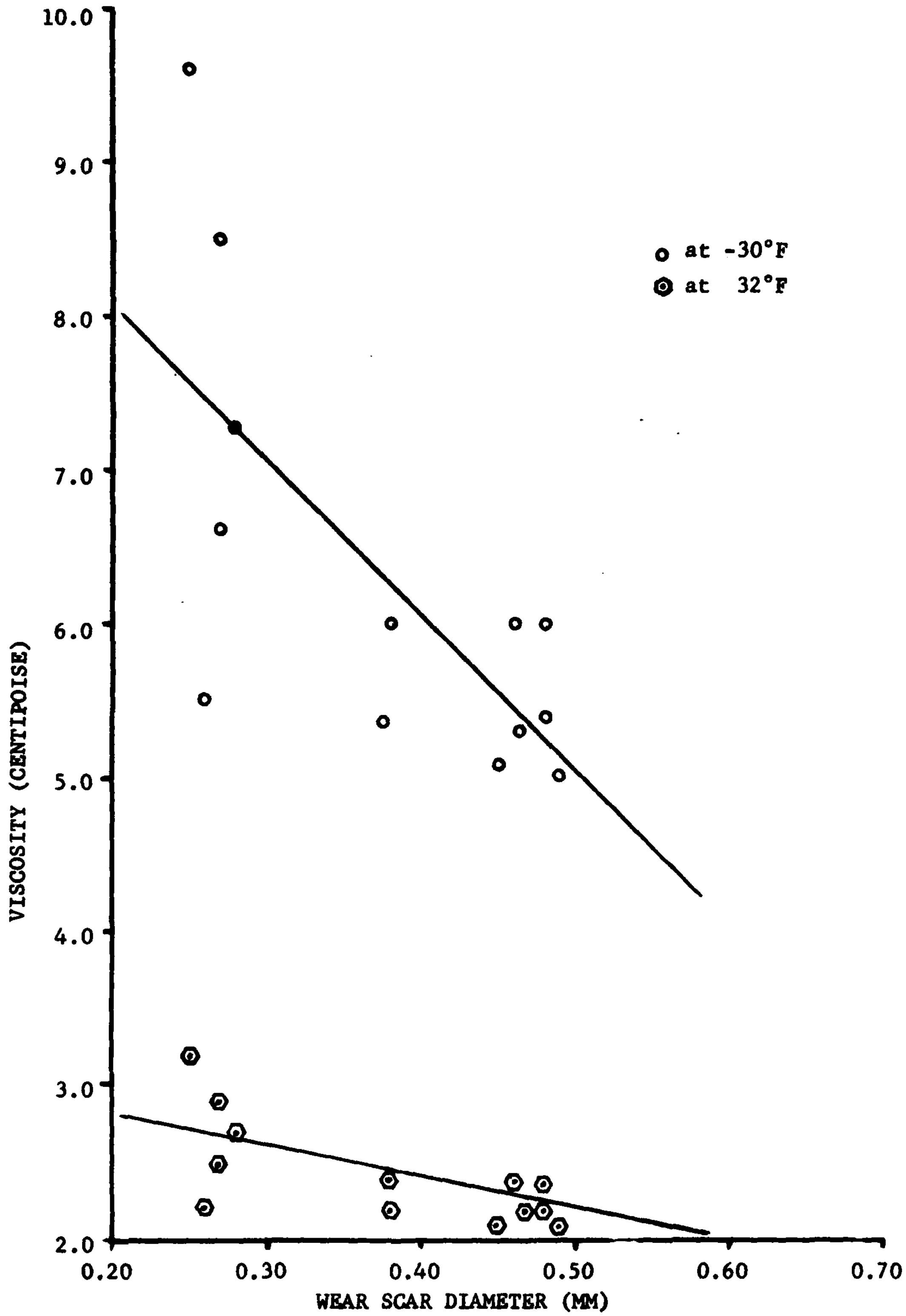

Figure 13. Viscosity vs WSD for Jet A-1 Fuels

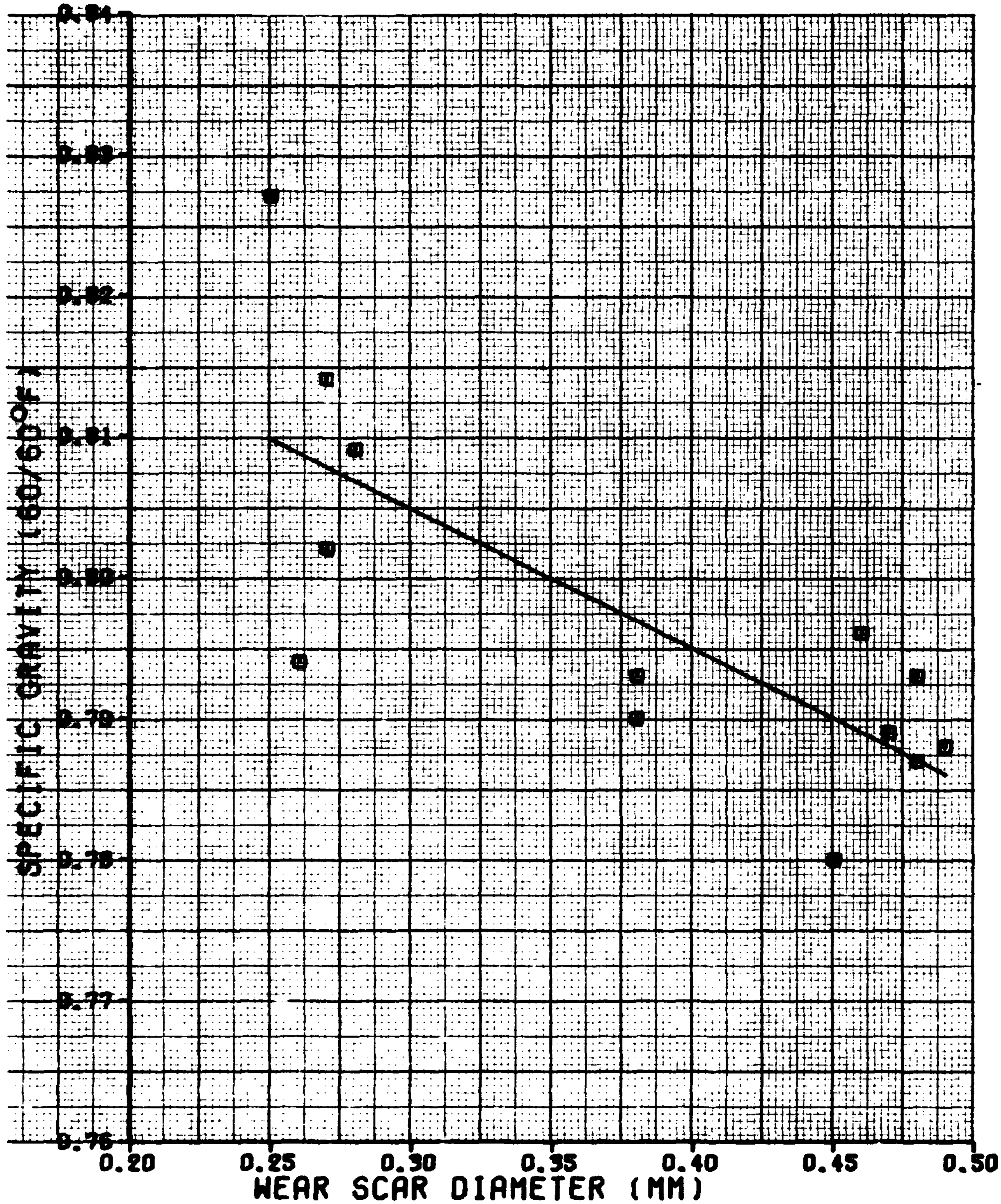

Figure 14. Specific Gravity vs WSD for Jet A-1 Fuels

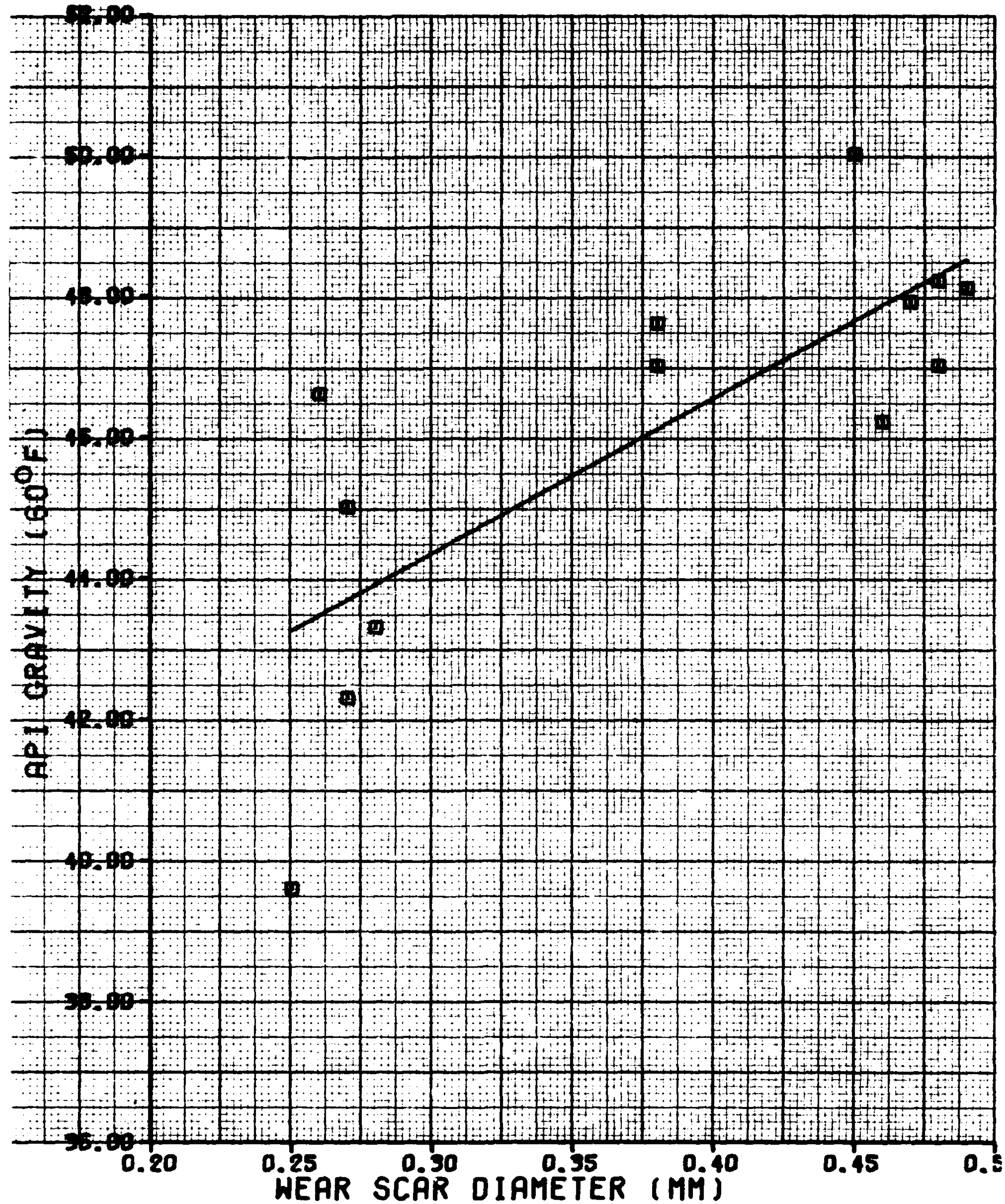

Figure 15. API Gravity vs WSD for Jet A-1 Fuels

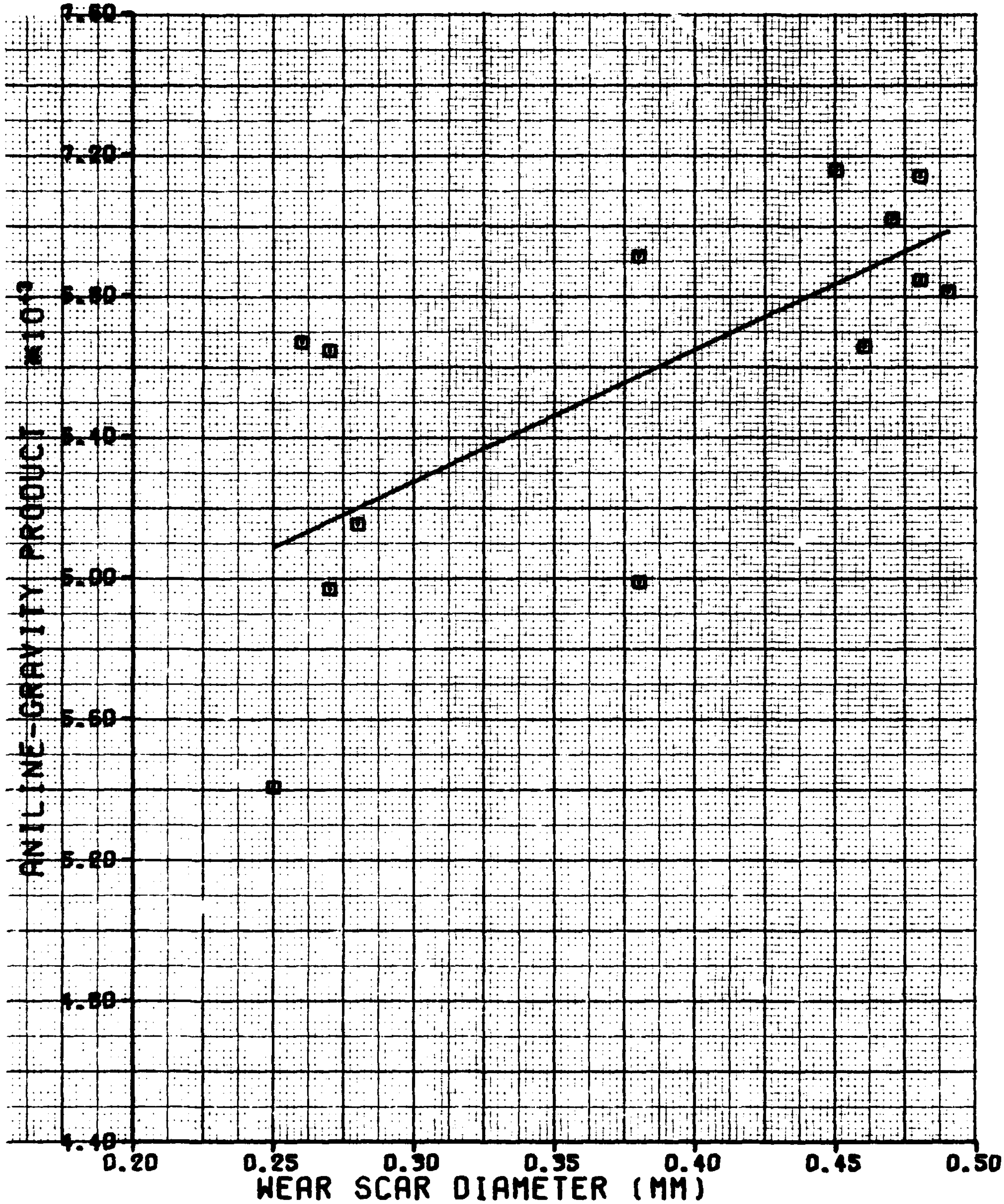

Figure 16. Aniline Gravity Product vs WSD for Jet A-1 Fuels

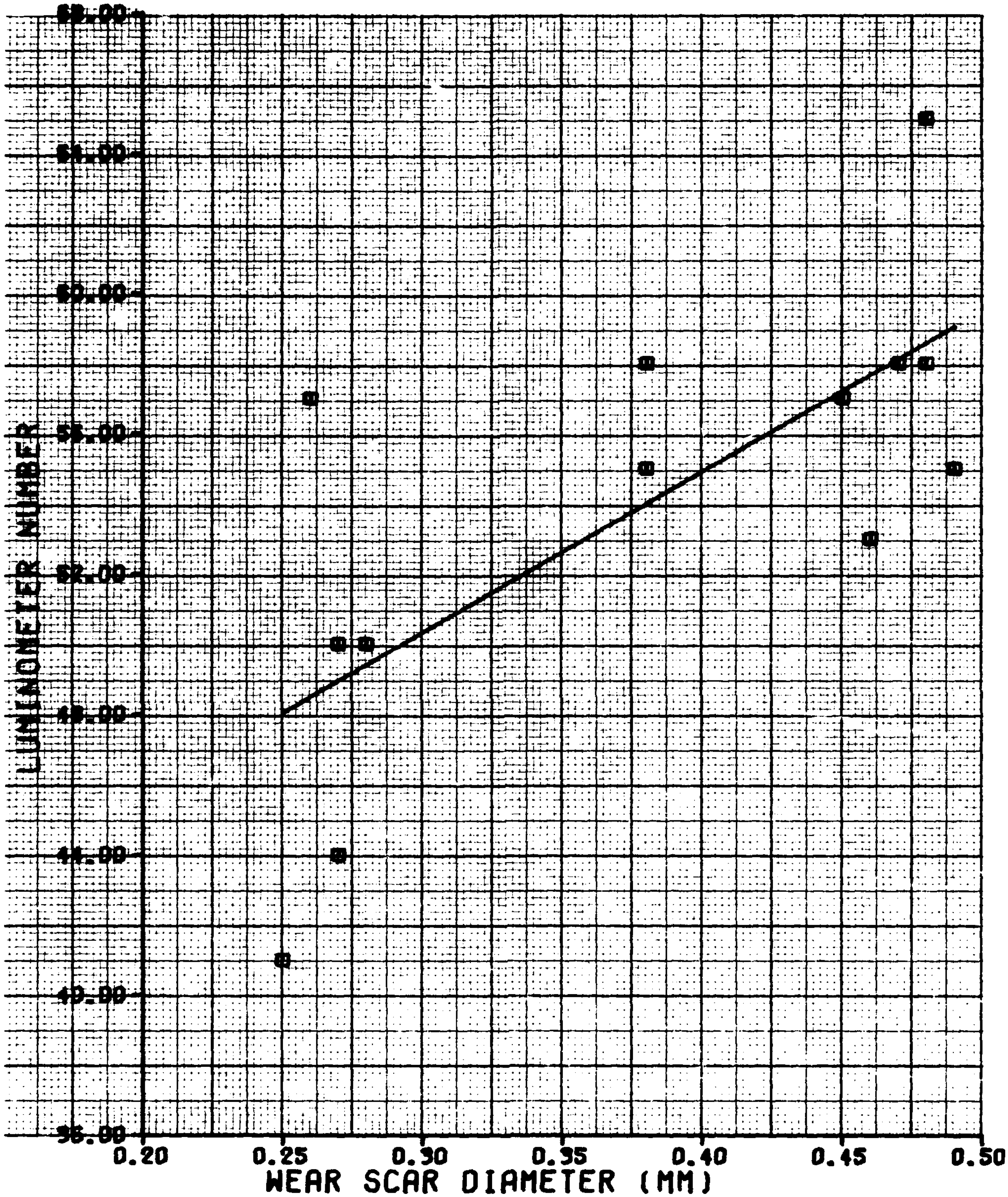

Figure 17. Luminometer Number vs WSD for Jet A-1 Fuels

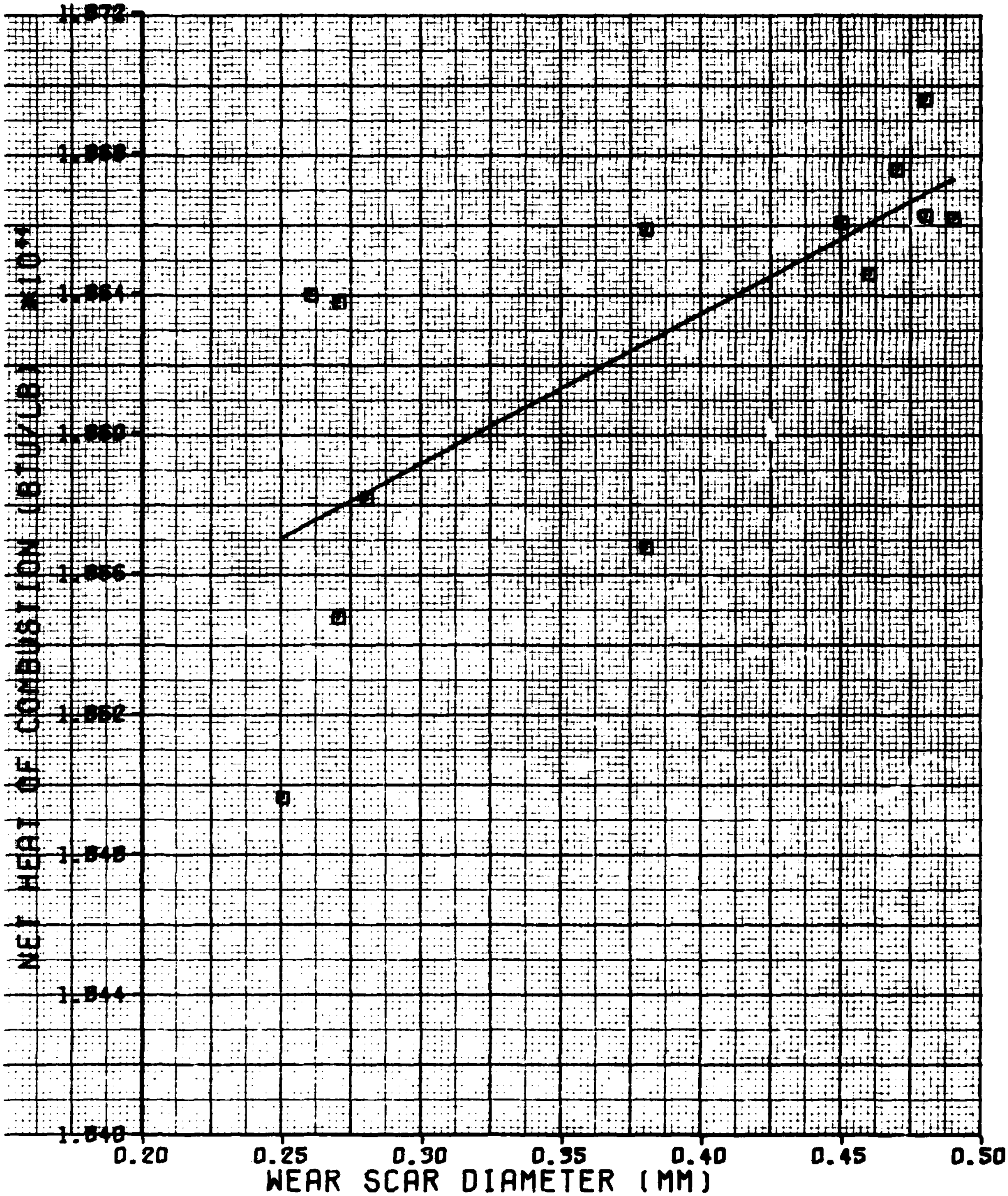

Figure 18. Net Heat of Combustion vs WSD for Jet A-1 Fuels

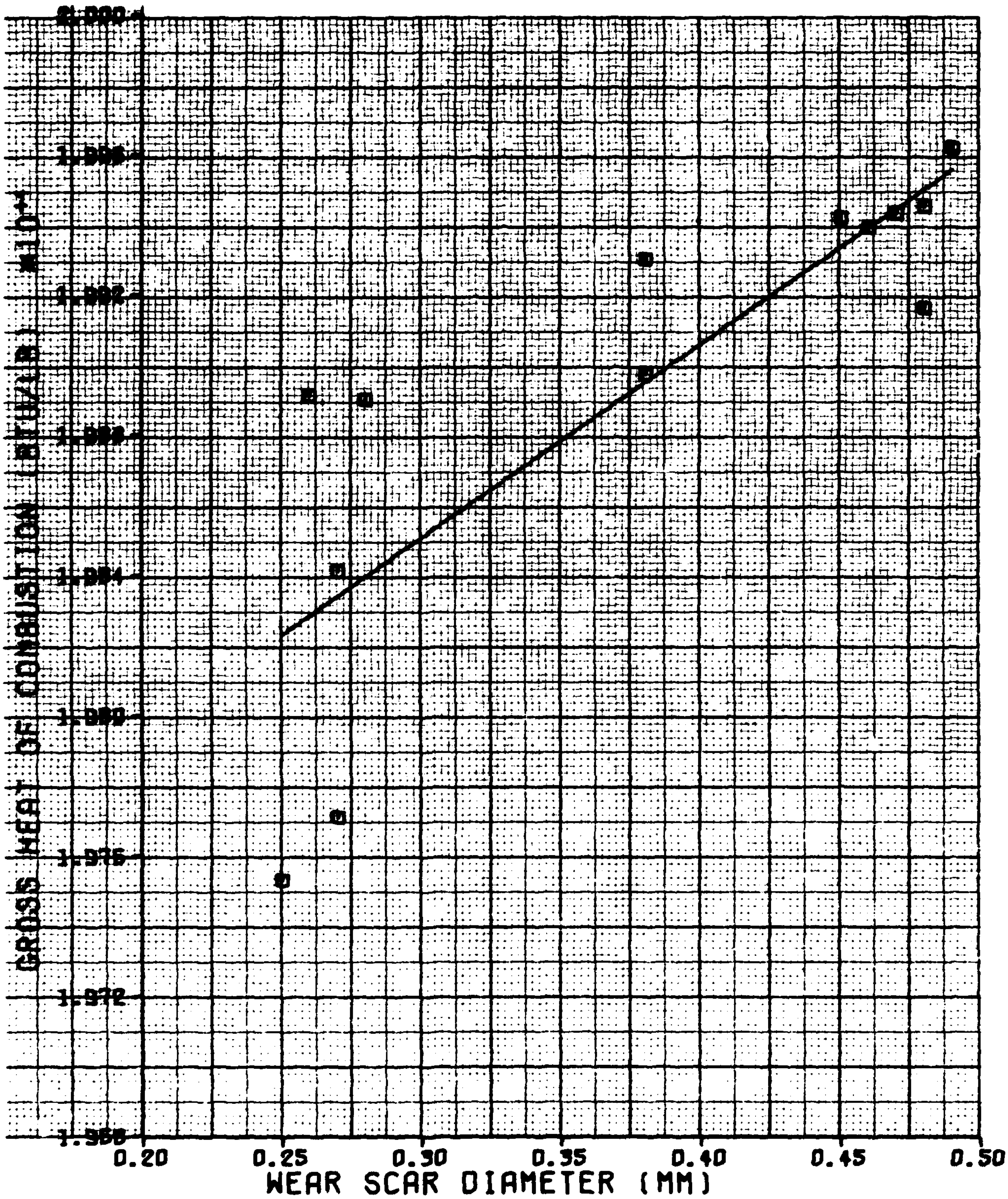

Figure 19. Gross Heat of Combustion vs WSD for Jet A-1 Fuels

molecular weight components in its heavy ends than a fuel with a low 90% Recovery B.P. The same reasoning holds true in a homologous series for the specific gravity and viscosity. Therefore, the fuels whose composition contains the higher molecular weight hydrocarbons will also have the higher specific gravity and viscosity. Since the regression lines for the relations in this group have negative slopes, the wear scar diameters become smaller as the proportion of high molecular weight components become larger. This implies that the Jet A-1 fuels which have high molecular weight chain hydrocarbons in their heavy ends will have better lubricity than those without the heavy ends.

The physical properties in Group B are also interrelated to the composition of the Jet A-1 fuels. The API gravity is inversely proportional to the specific gravity by the following formula from ASTM Test Method D287:

API Gravity = (141.5/sp gr 60/60F) - 131.5

Therefore, it is expected to correlate with wear scar diameter since the specific gravity has already been shown to correlate. The aniline-gravity product is simply the product of the aniline point and API gravity. The rank coefficient of the aniline point in its relation to wear scar diameter was .368 which shows it is independent at the 5% level of significance. However, since the API gravity was strongly dependent (rank coefficient .750), the product of the two properties was also dependent (rank coefficient .666) with WSD diameter.

The net heat of gross heat of combustion, and the luminometer number of a hydrocarbon fuel are also known to be related to its specific gravity[8]. As the specific gravity increases, the net heat of combustion, gross heat of combustion, and luminometer number of the fuel decrease. For all the physical properties in Group B, a decrease in their value corresponds to a decrease in wear scar diameter. This also implies, as in the case of Group A, that the Jet A-1 fuels which have the higher molecular weight hydrocarbons in their heavy ends have the best lubricity.

Additional data have been obtained from the gas chromatograph on the Jet A-1 fuels[9]. The % recovery at 400, 450, and 500°F for the Jet A-1 fuels is tabulated in Table 8 and plotted versus WSD in Figure 20. The rank coefficients for the relation between % recovery and WSD are .462, .522, and .675, respectively. At the 5% level of significance, the % recovery at 400 and 450 degrees are independent of WSD but the % recovery at 500 degrees is dependent on WSD. This indicates that the components in the fuel which have boiling points higher than 500°F are primarily responsible for improving the lubricity of the Jet A-1 fuels.

7.2 JP-4 FUELS

Nineteen JP-4 fuels have been tested on the Ball-on-Cylinder and the results are listed in Table 9. The physical properties of these fuels are located in Table 10[10].

The physical properties of each fuel and its wear scar diameter were tested for independence using the Spearman Rank Analysis.

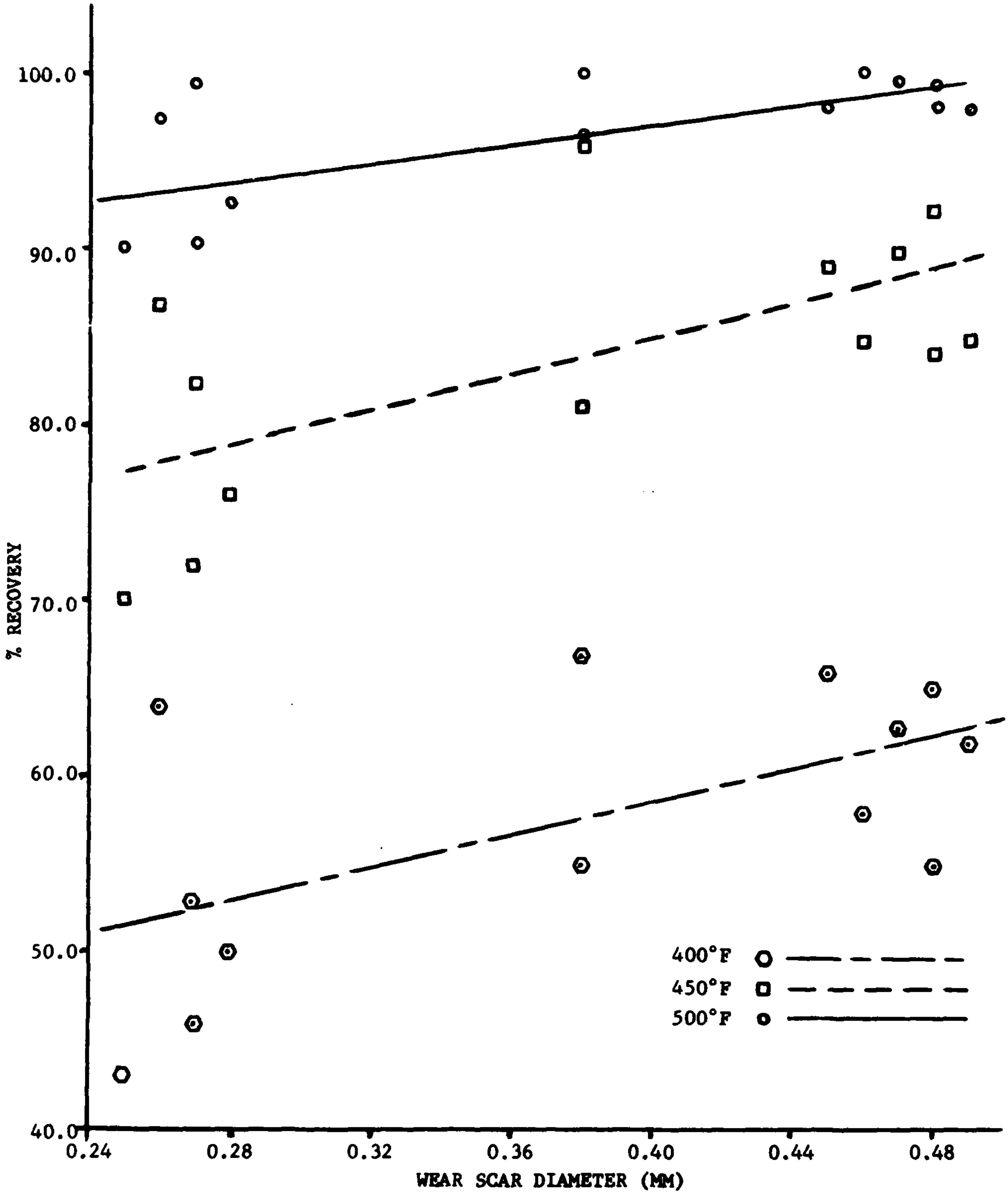

Figure 20. Percent Recovery vs WSD for Jet A-1 Fuels

TABLE 8

Percent Recovery of Jet A-1 Fuels
at
400°, 450°, and 500°F

JET A-1 FUEL	% RECOVERY AT*		
	400°F	450°F	500°F
171-1	62.0	85.0	98.0
171-2	64.0	87.0	97.5
171-3	63.0	90.0	99.7
171-5	58.0	85.0	100.0
271-1	55.0	84.0	98.4
271-3	66.0	89.0	98.2
371-1	55.0	81.0	96.5
371-2	67.0	96.3	100.0
471-1	65.0	92.5	99.3
970-1	50.0	76.0	92.5
970-2	46.0	72.0	90.2
970-3	43.0	70.0	90.0
1170-2	53.0	82.3	99.5

* Using ASTM D 2887, Boiling Range Distribution of Petroluem Fractions by Gas Chromotography

TABLE 9

BALL-ON-CYLINDER RESULTS FOR JP-4 FUELS

FUEL	WEAR SCAR DIAMETER* (mm)	COEFFICIENT* OF FRICTION
JP4-1	.29	.13
JP4-2	.26	.13
JP4-3	.40	.16
JP4-4	.42	.14
JP4-5	.395	.14
JP4-6	.35	.15
JP4-7	.39	.14
JP4-8	.47	.13
JP4-9	.44	.14
JP4-10	.24	.14
JP4-11	.26	.14
JP4-12	.31	.14
JP4-13	.42	.14
JP4-14	.26	.15
JP4-15	.46	.13
JP4-16	.27	.13
JP4-17	.27	.15
JP4-18	.23	.15
JP4-19	.34	.15

*Mean of three trials; Operating Conditions: 1000 gm load, 240 rpm, 75°F, .5 ft^3/min, indirect flowrate of dry air, AISI 52100, steel specimens (ball, 60-63 Rockwell C and Cylinder, 22.5 Rockwell C) and 32 min. test time.

TABLE 10

PHYSICAL PROPERTIES OF JP-4 SURVEY FUELS

METHOD	PROPERTY	SPC. LIMIT	JP4-1	JP4-2	JP4-3	JP4-4	JP4-5	JP4-6	JP4-7	JP4-8	JP4-9	JP4-10	JP4-11	JP4-12	JP4-13	JP4-14	JP4-15	JP4-16	JP4-17	JP4-18	JP4-19
	COMPOSITION																				
D1319	Aromatics (Vol %)	25	10.8	10.8	9.3	8.9	8.3	24.8	9.7	12.6	17.8	14.6	12.8	12.2	11.8	8.7	11.3	11.6	21.6	9.9	6.9
D1319	Olefins (Vol %)	5.0	0.8	0.8	1.0	1.4	1.2	1.1	1.1	0.5	1.0	0.7	0.8	0.8	0.6	0.5	1.0	0.6	0.9	0.8	1.3
D1219	Sulfur, Mercaptan (Wt%)	.001																			
D484	Doctor Test (P=Pos, N=Neg)		N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
D1260	Sulfur, Total (Wt %)	0.4	.06	.03	.02	.08	.04	.01	.02	.01	.06	.07	.14	.04	.09	.10	.01	.01	.03	.02	.04
	Basic Nitrogen (ppm) [1]		-	-	0.2		1.3	0.0	0.7	0.6	-	-	16.3	7.4 -	-	-	-	-	0.4	-	-
	Iron (ppb)		-	8	49	-	14	-	145	-	-	-	-	-	-	27	9	-	-	-	17
	Copper (ppb)		5	-	-	-	119	-	9	-	-	-	-	3	-	10	<3	-	-	-	4
	Zinc (ppb)		19	-	-	-	4	-	73	-	-	-	-	42	-	14	24	-	-	-	24
	Lead (ppb)		-	265	-	226	416	-	343	-	-	-	-	-	-	67	<3	-	-	-	540
	Carbon (Wt %) [2]		85.75	85.70	85.22	85.27	84.99	86.31	85.45	85.61	85.99	86.28	86.15	86.03	85.20	85.64	85.74	85.71	85.69	85.37	84.93
	Hydrogen (Wt %) [2]		14.33	14.42	14.68	14.67	14.94	13.75	14.55	14.30	13.94	13.61	13.81	13.94	14.74	14.31	14.25	14.16	14.16	14.54	14.77
	VOLATILITY																				
D86	Distillation Init. BP (°F)		155	142	136	127	126	160	130	140	142	144	143	144	126	167	144	134	116	138	130
	10% Rec (°F)		183	236	220	220	194	199	216	214	250	232	195	192	214	202	222	215	232	197	252
	20% Rec (°F)	290	195	260	235	286	220	212	248	234	280	256	217	208	256	216	246	242	272	222	279
	50% Rec (°F)	370	257	309	258	367	285	261	328	264	324	331	312	254	345	264	285	338	304	306	318
	90% Rec (°F)	470	440	407	417	435	426	344	445	318	394	430	446	364	437	438	360	440	358	413	421
	95% Rec (°F)																				
	Final BP (°F)		491	477	474	477	472	412	486	389	440	474	492	482	474	484	424	487	425	457	450
	Residue (%)	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Loss (%)	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Recovery at 400°F (%)		80	89	89	75	81	97	75	-	92	72	73	93	73	79	97	73	96	86	79
D287	Gravity API (60°F)	45.-57.	53.9	52.7	55.9	50.6	56.8	54.4	51.9	56.9	51.3	47.2	47.2	55.4	52.6	54.1	53.1	51.6	51.0	54.4	56.1
D1298	Gravity, Specific (60/60°F)		.763	.768	.755	.777	.751	.761	.772	.751	.774	.792	.792	.757	.769	.762	.767	.773	.775	.761	.754
D323	Vapor Pressure (Lb Reid)	2.0-3.0	2.5	2.3	2.7	2.2	2.9	2.2	2.5	2.2	2.1	2.2	2.2	2.3	2.5	1.8	2.2	2.6	2.5	2.4	2.2
	FLUIDITY																				
D2386	Freezing Point (°F)	-72	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	B-90	-84
D445	Viscosity at -30°F (cst)		2.2	2.7	2.0	3.8	2.2	1.6	3.1	1.8	2.8	3.2	2.9	1.9	3.1	2.4	2.2	3.1	2.3	2.6	2.9
	at +32°F (cst)		1.2	1.4	1.1	1.7	1.2	0.9	1.5	1.0	1.4	1.6	1.5	1.0	1.5	1.3	1.2	1.5	1.2	1.3	1.4
	at 100°F (cst)		0.8	0.8	0.7	1.0	0.8	0.6	0.9	0.7	0.8	0.9	0.9	0.7	0.9	0.8	0.7	0.9	0.8	0.8	0.9
	COMBUSTION																				
D1405	Aniline-Gravity Product	5250	7169	7196	7491	7337	8122	5902	7344	7397	6669	5947	5806	6925	7522	7439	6797	7172	6018	7507	8667
D1405	Net Heat of Combustion (Btu/lb)[3]	18400	18725	18733	18766	18741	18829	18599	18750	18757	18672	18596	18571	18702	18758	18748	18694	18733	18600	18767	18886
	Net Heat of Combustion (Btu/lb)[4]		18786	18656	18697	18738	18703	18574	18773	18780	18651	18580	18544	18673	18718	18747	18712	18685	18584	18706	18870
D240	Gross Heat of Combustion (Btu/lb)[5]		20093	19972	20037	20069	20067	19829	20100	20086	18659	19822	19834	19945	20063	20053	20012	19975	19875	20033	20218
	Aniline Point (°F)		133.0	136.5	134.0	145.0	143.0	108.5	141.5	130.0	130.0	126.0	123.0	125.0	143.0	137.5	128.0	139.0	118.0	138.0	154.5
D1740	Luminometer No.	60	78	76	80	69	85	63	78	77	61	58	58	79	74	83	82	71	63	82	94
D1322	Smoke Point		27.0	27.0	28.0	27.0	27.0	18.0	27.0	27.0	25.0	21.0	21.0	21.0	27.0	25.0	25.0	24.0	20.0	27.0	23.0
D1655	Smoke-Volatility Index	52.0	60.6	64.4	65.4	58.5	61.0	58.7	58.5	-	63.6	51.2	51.7	60.1	57.7	58.2	65.7	54.7	60.3	63.1	56.2
	CONTAMINANTS																				
D381	Existent Gum (mg/100ml)	7	0.4	1.2	1.8	2.0	0.0	2.0	0.6	0.0	0.0	0.8	6.8	2.2	1.2	4.0	2.4	1.8	1.2	2.2	2.0

1 Universal Oil Products Method 313-58
2 Averaged Values
3 Calculated from equations in ASTM D1405
4 Calculated using equation: Heat of Combustion = Gross Heat, Btu/lb - 91.23 x % Hydrogen
5 Average value corrected for sulfur content

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The rank coefficients for the various relations are tabulated in Table 11. For 19 fuels and a 5% level of significance, K (α_1, n) = -.456 and K (α_2, n) = + .456.

Several physical properties are of primary interest due to the historical reasons discussed in Section 7.1. They are aromatic content, sulphur content, viscosity, and thermal stability (breakpoint).

The sulphur content of the fuels ranged from .01 to .14 wt %. Its relationship to WSD is shown in Figure 21. The regression line is also on this graph. The rank coefficient for this relationship was -.223; however, as mentioned in the case of the Jet A-1 fuels, the reproducibility of the sulphur test can affect the validity of the rank analysis. Therefore, the test for the independence of the sulphur content of the fuel and its wear scar diameter is inconclusive.

The aromatic content of the JP-4 fuels ranged from 6.9 to 24.8 volume % and the regression line from its relationship with WSD is shown in Figure 22. The rank correlation coefficient between aromatic content and wear scar diameter was -.017. The two items do not correlate.

The viscosity of the JP-4 fuels is determined at three different temperatures: -30°F, 32°F, and 100°F. They are plotted versus wear scar diameter for each case in Figure 23, which also includes the regression lines. The rank coefficients for the three cases were -.209,

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TABLE 11

PHYSICAL PROPERTY-WSD RANK CORRELATION COEFFICIENTS FOR JP-4 FUELS

PHYSICAL PROPERTY	STANDARD ERROR OF ESTIMATE FOR Y	RANK COEFFICIENT
Aromatics	4.44	-.0171
Olefins	.235	.348
Sulphur, Total	.034	-.223
Carbon (wt %)	.360	-.310
Hydrogen (wt %)	.345	.278
D86 - Init. BP	11.8	-.247
D86 - 10% Rec	18.6	.156
D86 - 20% Rec	25.1	.241
D86 - 50% Rec	36.1	.025
D86 - 90% Rec	36.1	-.365
D86 - Final BP	26.1	-.444
Gravity, API	2.6	-.269
Gravity, Spec.	.011	.272
Viscosity @ -30°F	.55	-.209
Viscosity @ 32°F	.21	-.211
Viscosity @ 100°F	.10	-.178
Aniline Gravity Product	705.5	.192
Net Heat Comb*	72.0	.183
Gross Heat of Comb	.03	.305
Aniline Point Nr	10.3	.157
Luminometer Nr	9.6	.104
Existent Gum	1.42	-.327
Breakpoint**	24.1	.060

* Calculated values from equations in ASTM D1405

** JFTOT results from reference 10

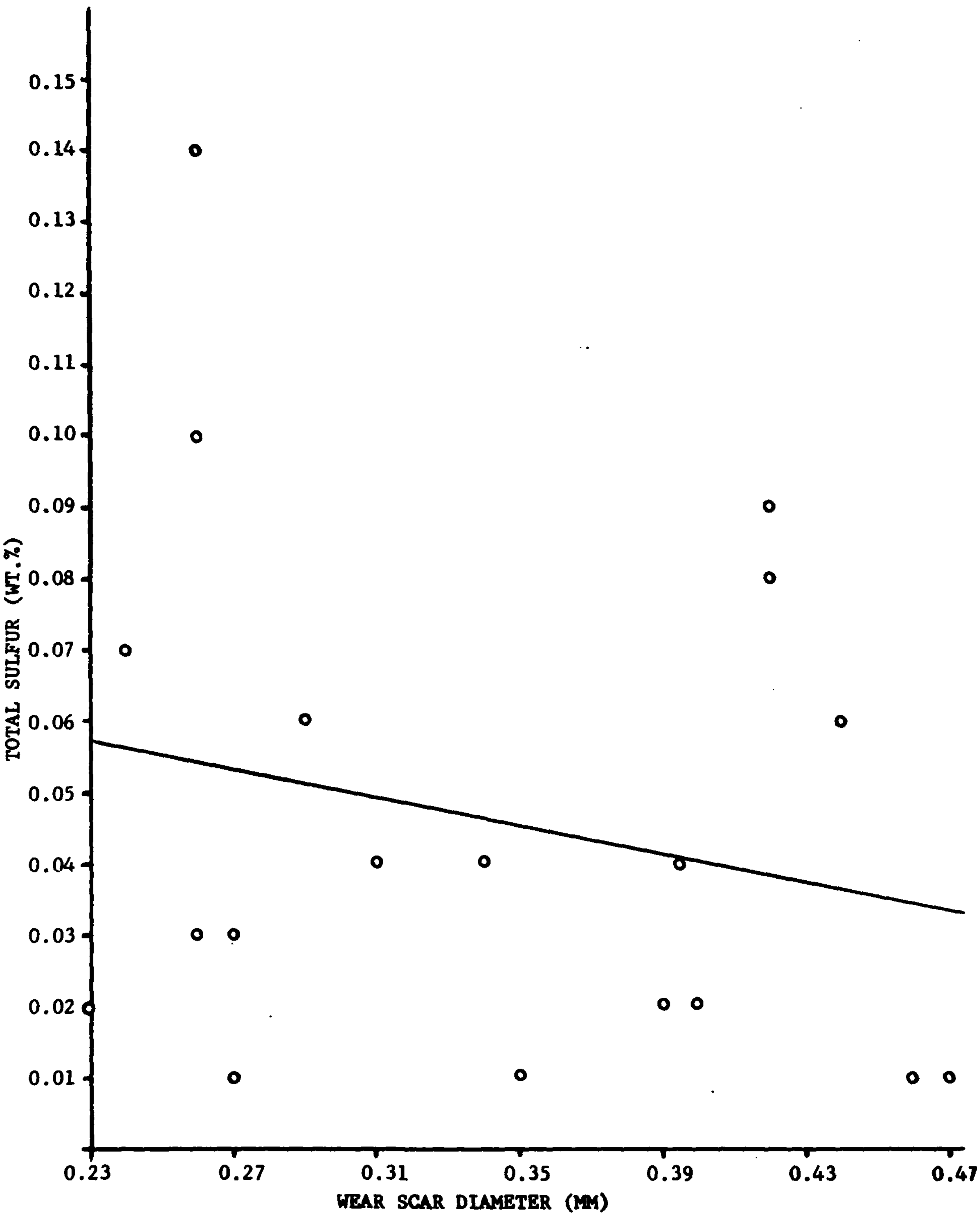

Figure 21. Total Sulfur vs WSD for JP-4 Fuels

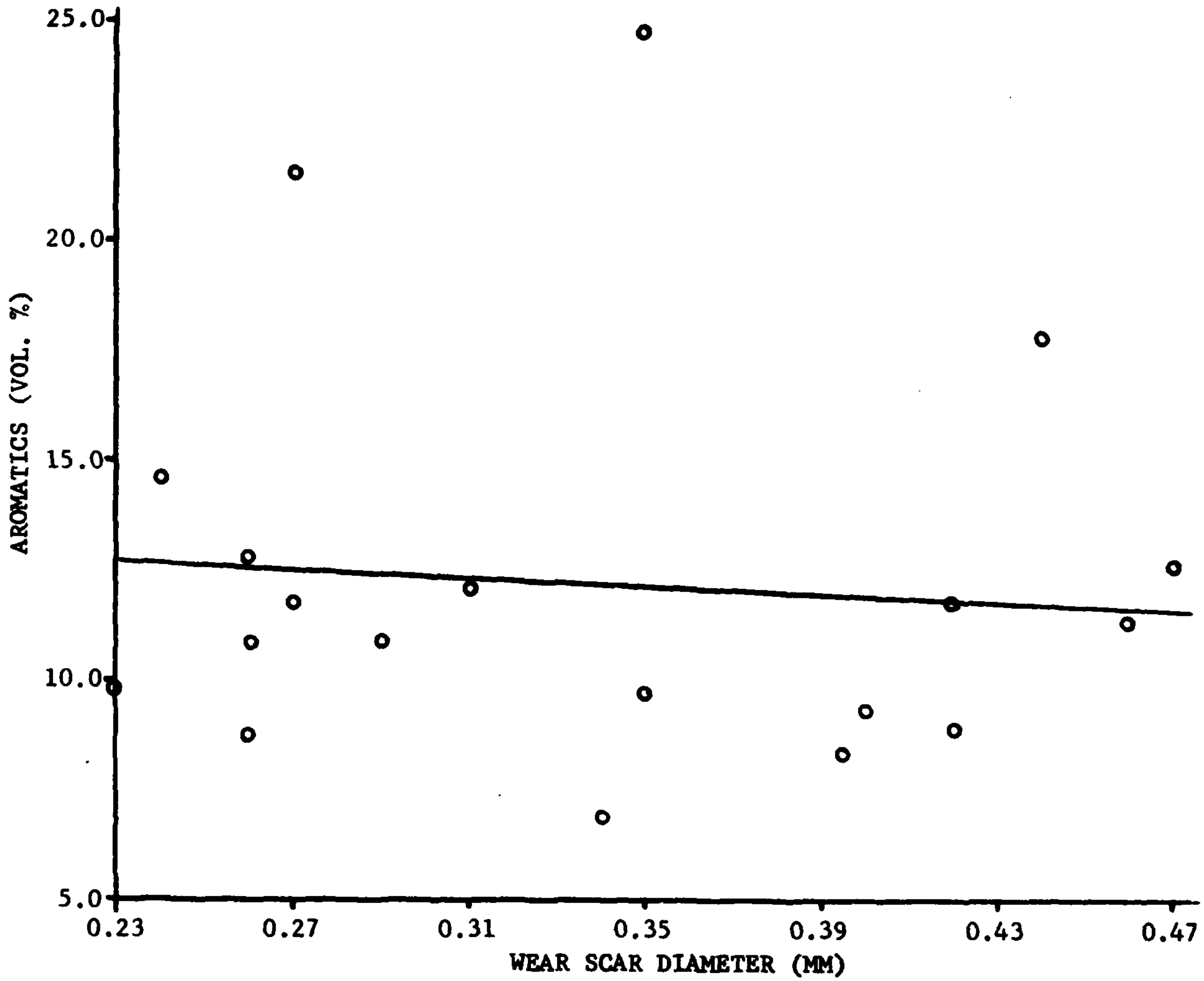

Figure 22. Aromatics vs WSD for JP-4 Fuels

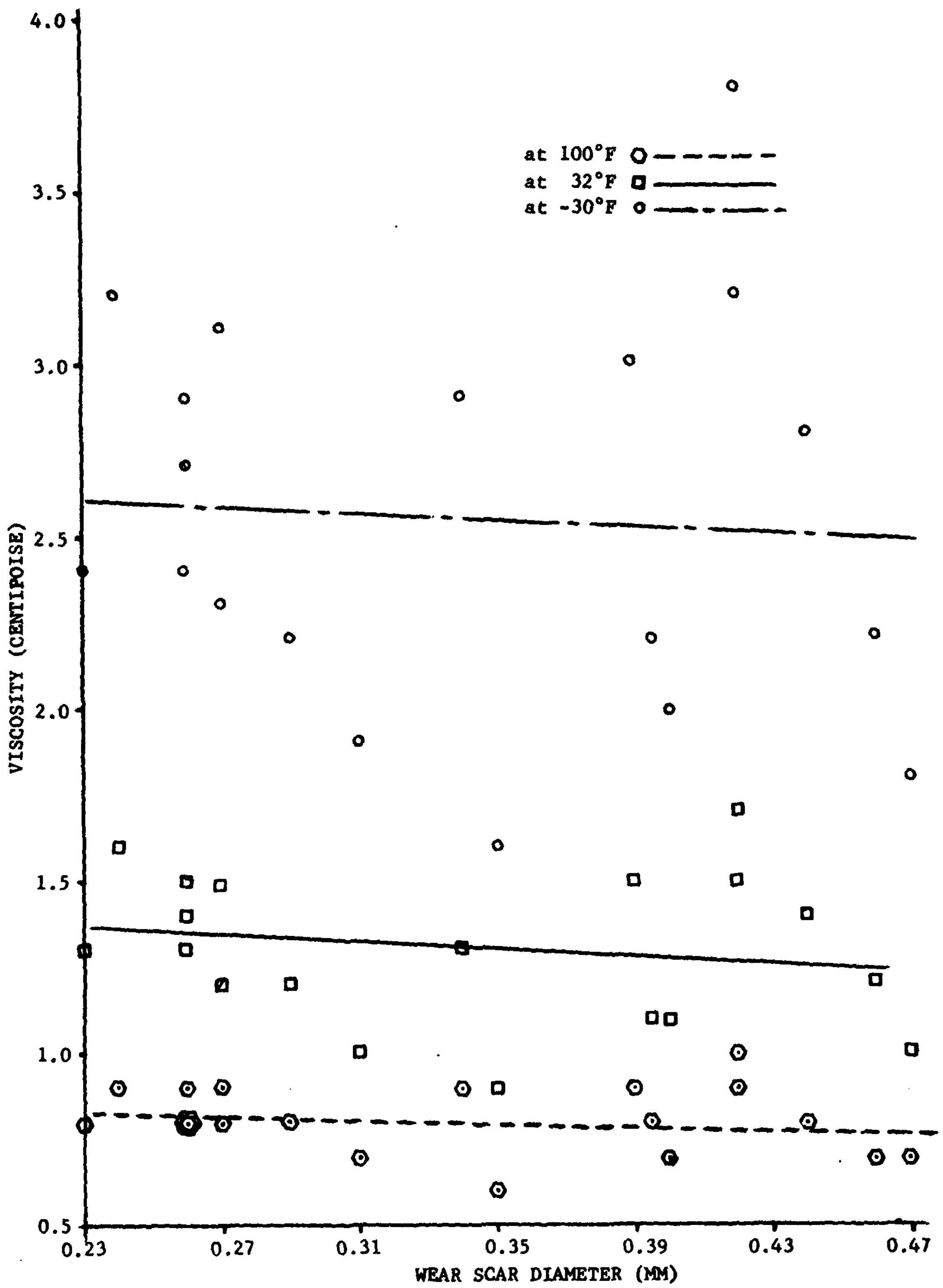

Figure 23. Viscosity vs WSD for JP-4 Fuels

-.211, -.178, respectively. Therefore, the viscosity is independent of wear scar diameter at the 5% level of significance for the three cases.

The last property of interest is the thermal stability breakpoint which is plotted versus wear scar diameters in Figure 24 along with the regression line. The rank coefficient was .060 for this relation. As in the case of the Jet A-1 fuels, the breakpoint of the Jet A-1 fuels is independent of wear scar diameter at the 5% level of significance.

The remaining rank correlation coefficients in Table 11 for the relationships between the physical properties and wear scar diameters produced no correlations. This is not totally surprising since the JP-4 fuels contained corrosion inhibitors whereas the Jet A-1 fuels did not.

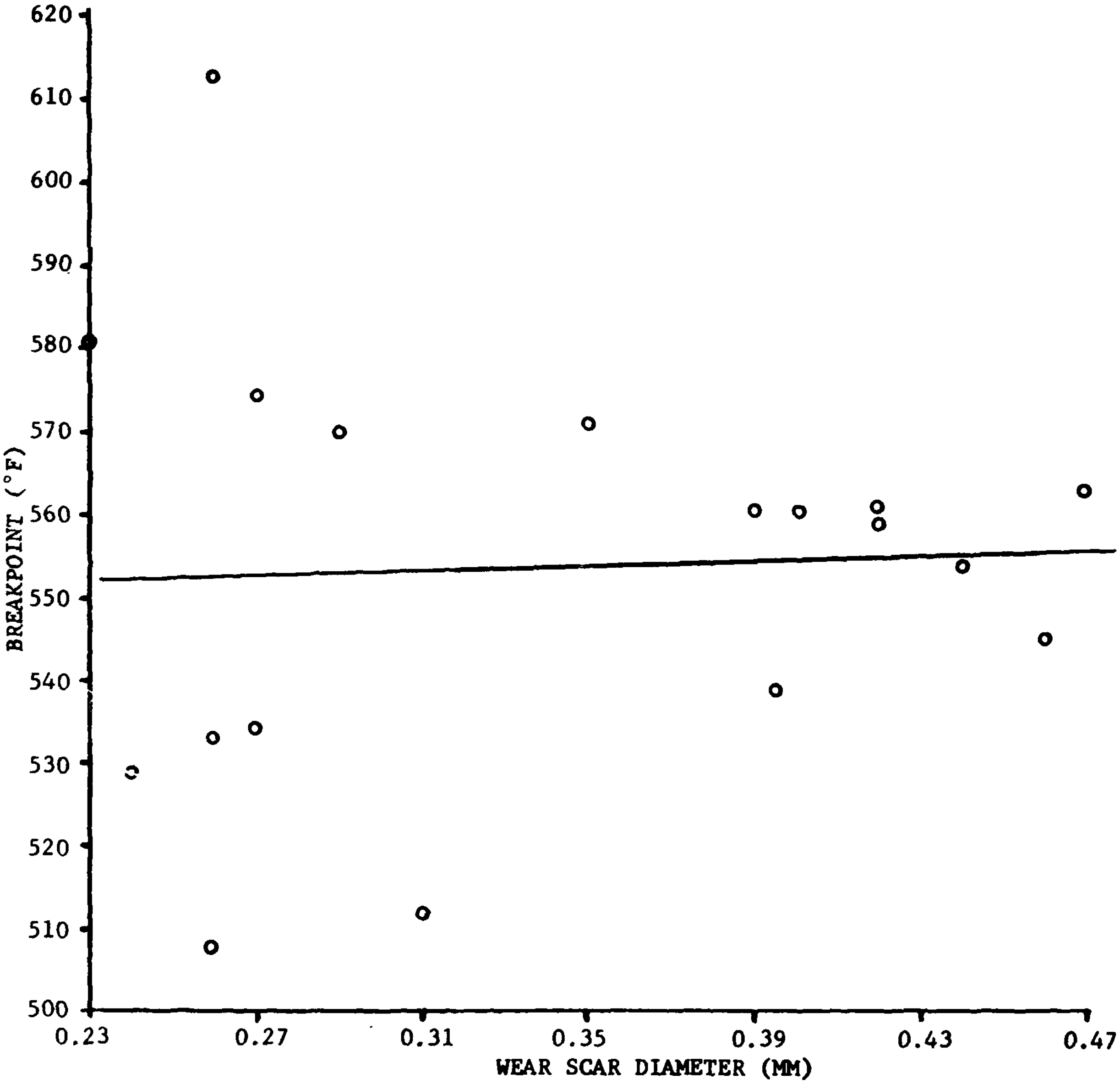

Figure 24. Thermal Stability vs WSD for JP-4 Fuels

8.0 CONCLUSIONS

a. The repeatability of the wear scar diameter measurement from the Ball-on-Cylinder rig varied from 0.0% to 9.1% which is acceptable. The reproducibility based on limited data ranged from 0.0% to 19.1%.

b. The wear scar diameter measurement from the Ball-on-Cylinder device is a more sensitive indicator of the lubricity of Jet A-1 and JP-4 fuels than its calculated coefficient of friction.

c. The lubricity data on the Jet A-1 fuels from the Ball-on-Cylinder and Bendix-CRC Lubricity Simulator indicate the two test devices correlate.

d. The metallurgy of the test specimens for the Ball-on-Cylinder was AISI-52100 Steel and for the Bendix-CRC Lubricity Simulator was hard-anodized aluminum. It appears that the difference in metallurgy of the test specimens between the rigs is not a major parameter which affects the correlation between the lubricity test rigs.

e. The aromatic content and the thermal stability of the Jet A-1 and JP-4 fuels were found not to be related to the fuels lubricity.

f. The lubricity of the Jet A-1 fuels is related to the amount of components in the fuel which have boiling points over 500°F.

9.0 FUTURE WORK

As part of the ASCC Lubricity Program, the British will test the Jet A-1 and JP-4 fuels discussed in this report on the Lucas Dwell Meter for lubricity. Once these results are obtained, a possible correlation between the Ball-on-Cylinder and the Lucas Dwell Meter will be examined.

The next phase of the Air Force program on lubricity is to evaluate the effectiveness of corrosion inhibitors as lubricity agents on the Ball-on-Cylinder rig. The study will involve testing the inhibitors in a base fluid at different concentrations and temperatures.

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